Faculty of Electrical Engineering

MASTER THESIS

Reactive Power Compensation

Author:
Jakub Kępka

Supervisor:
PhD. Zbigniew Leonowicz

DRAFT

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1. Acknowledgments

2. Introduction

Over the last few years, the interest in reactive power compensation has been growing, mainly because of the way in which energy supplier charge a customer for reactive power. Moreover, the energy price is growing, what force the industry plants and individual customers to minimize energy consumption, including reactive power. The aim is to minimize reactive power flow in supplying and distribution systems , eliminate or minimize the charge for reactive power as well as aspire to active energy limitation, in result, reducing fare for electrical energy. In the matter of fact, the energy providers wants they customers to compensate reactive power. Energy suppliers determine the value of tgφ which has to be kept in order to avoid paying for reactive power.

There are few solutions, that allow handle the problem of reactive power compensation. One of them is reactive power compensator basing on power capacitors. This is the most popular compensating device, mainly because of economical reasons, they are relatively cheap comparing with i.e. active filters or compensation by means of electric motors. That is one of the reasons, for which Elektrotim company proposed the master`s thesis topic – “Design of automatic capacitor bank” They want to launch brand new product to their offer, that is Automatic Capacitor bank.

To begin with, the aim of the project was to design automatic detuned capacitor bank for reactive power compensation company with rated power of 200kVar, rated voltage of 400V and detuning factor p=7%. One out of few assumptions was to find supplier who offers low prices and average quality as well as the one, who offers very good quality of the power factor correction equipment in order to meet the requirements of Elektrotim company customers.

The first most important thing before design process get started is to familiarize oneself with standards. Then, knowing what are the requirements regarding capacitor banks in compliance with standards I could proceed to the market survey and compare the elements capacitor bank regarding price, features and quality. Next step is to perform all necessary calculations in order to buy the capacitor bank equipment with proper rating. After that, when all the elements will be ordered I design main and control circuits as well as equipment layout. As a last steps, technical documentation and test program has to be done.

3. Power theory

3.1 Active Power

“Power is a measure of energy per unit time. Power therefore gives the rate of energy consumption or production. The units for power are generally watts (W). For example, the watt rating of an appliance gives the rate at which it uses energy. The total amount of energy consumed by this appliance is the wattage multiplied by the amount of time during which it was used; this energy can be expressed in units of watt-hours (or, more commonly, kilowatt-hours). The power dissipated by a circuit element—whether an appliance or simply a wire—is given by the product of its resistance and the square of the current through it:$\mathrm{P} = I^2\mathrm{R}$. The term “dissipated” indicates that the electric energy is being converted to heat. This heat may be part of the appliance’s intended function (as in any electric heating device), or it may be considered a loss (as in the resistive heating of transmission lines); the physical process is the same. Another, more general way of calculating power is as the product of current and voltage: $\mathrm{P} = \mathrm{I}\,V$. For a resistive element, we can apply Ohm’s law ($\mathrm{P} = \mathrm{I} \cdot \mathrm{V}$) to see that the formulas $\mathrm{P} = I^2\mathrm{R}$ and $\mathrm{P} = I \quad \mathrm{V}$ amount to the same thing:” [1]

$$\mathrm{P} = IV = I(IR) = I^2\mathrm{R} \ (1)$$

3.2 Complex power

“Applying the simple formula $\mathrm{P} = \mathrm{I} \cdot \mathrm{V}$ becomes more problematic when voltage and current are changing over time, as they do in a.c. systems. In the most concise but abstract notation, power, current, and voltage are all complex quantities, and the equation for power becomes [1]

$$\mathrm{S} = I^*\mathrm{V} \ \ (2)$$

where S is the apparent power and the asterisk denotes the complex conjugate of the current I, meaning that for purposes of calculation, the sign (positive or negative) of its imaginary component is to be reversed. All this ought to make very little sense without a more detailed discussion of complex quantities and their representation by phasors. In the interest of developing a conceptual understanding of a.c. power, let us postpone the elegant mathematics and begin by considering power, voltage, and current straightforwardly as real quantities that vary in time. The fundamental and correct way to interpret the statement $P = I \cdot V$ when I and V vary in time is as a statement of instantaneous conditions. Regardless of all the complexities to be encountered, it is always true that the instantaneous power is equal to the instantaneous product of current and voltage. In other words, at any instant, the power equals the voltage times the current at that instant. This is expressed by writing each variable as a function of time, [1]

$$P(t) = I(t) \cdot V(t) \quad (3)$$

where the t is the same throughout the equation (i.e., the same instant).

“However, instantaneous power as such is usually not very interesting to us. In power systems, we generally need to know about power transmitted or consumed on a time scale much greater than 1/60 of a second. Therefore, we need an expression for power as averaged over entire cycles of alternating current and voltage. Consider first the case of a purely resistive load. Voltage and current are in phase; they are oscillating simultaneously. The average power (the average product of voltage and current) can be obtained by taking the averages (rms values) of each and then multiplying them together [1]. Thus,

$$P_{ave} = I_{RMS} \cdot V_{RMS} \quad \text{(resistive case)} \quad (4)$$

Power for the resistive case is illustrated in figure below. But now consider a load with reactance. The relative timing of voltage and current has been shifted; their maxima no longer coincide. In fact, one quantity is sometimes negative when the other is positive. As a result, the instantaneous power transmitted or consumed (the product of voltage and current) is sometimes negative. This is shown on Figure 1. We can interpret the negative instantaneous power as saying that power flows “backwards” along the transmission line, or out of the load and back into the generator. [1]

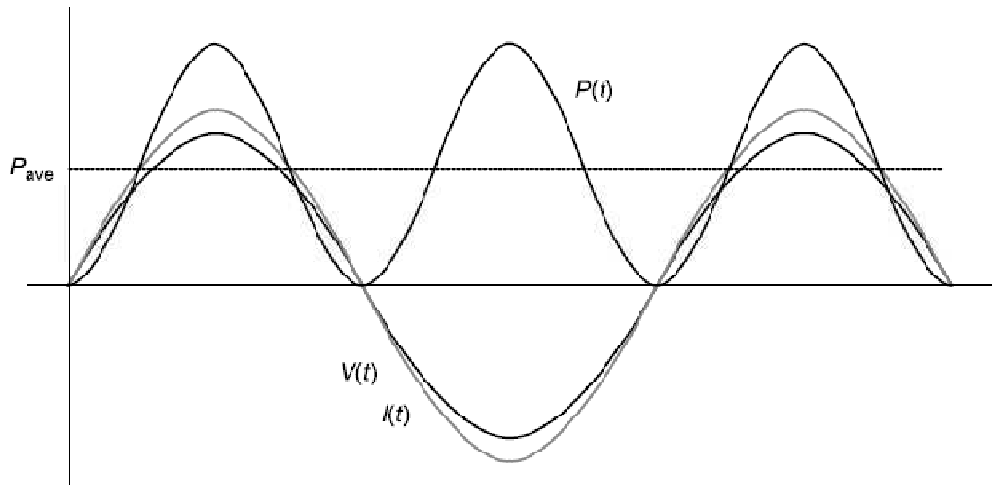


Fig. 1 Power as the product of voltage and current, with voltage and current in phase, source [1]

The energy that is being transferred back and forth belongs to the electric or magnetic fields within these loads and generators. Since instantaneous power is sometimes negative, the average power is clearly less than it was in the resistive case. But just how much less? Fortunately, this is very easy to determine: the average power is directly related to the amount of phase shift between voltage and current. Here we skip the mathematical derivation and simply state that the reduction in average power due to the phase shift is given by the cosine of the angle of the shift:

$$P_{ave} = I_{RMS} \cdot V_{RMS} \cdot \cos\varphi$$

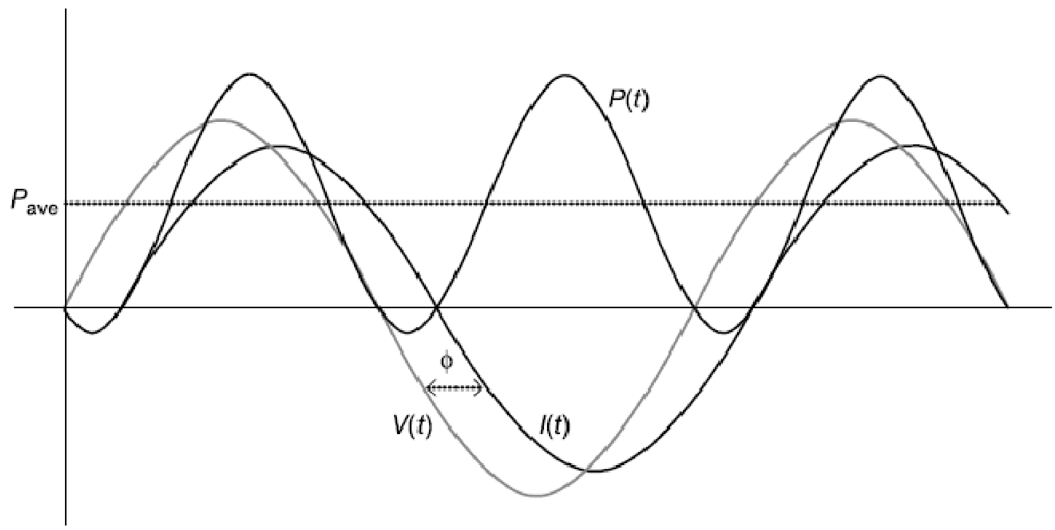


Fig. 2. Power Power as the product of voltage and current, with current lagging behind voltage by a phase angle Φ. , source [1]

“The factor of cosφ is called the power factor, often abbreviated p.f. This same equation can also be written as

$$P_{ave} = \frac{1}{2} I_{max} \cdot V_{max} \cdot \cos\varphi \quad (5)$$

which is identical because each rms value is related to the maximum value (amplitude) by a factor of $1/\sqrt{2}$. This equation is true for any kind of load. In the special case where there is only resistance and no phase shift, we have φ=0 and cosφ=0, so there is no need to write down the cos f, and we get the formula from the previous page. In another special case where the load is purely reactive (having no resistance at all), the phase shift would be φ=90 and cosφ=0, meaning that power only oscillates back and forth, but is not dissipated (the average power is zero). The average power corresponds to the power actually transmitted or consumed by the load. It is also called real power, active power or true power, and is measured in watts.
There are other aspects of the transmitted power that we wish to specify. The product of current and voltage, regardless of their phase shift, is called the apparent power, denoted by the symbol S. Its magnitude is given by” [1]

$$S = I_{RMS} \cdot V_{RMS} \quad (6)$$

“Although apparent and real power have the same units physically, they are expressed differently to maintain an obvious distinction. Thus, the units of apparent power are called volt-amperes (VA).” [1]

“Apparent power is important in the context of equipment capacity. Actually the crucial quantity with respect to thermal capacity limits is only the current. In practice, though, the current is often inconvenient to specify. Since the operating voltage of a given piece of equipment is usually quite constant, apparent power is a fair way of indicating the current. The point is that apparent power is a much better measure of the current than real power, because it does not depend on the power factor. Thus, utility equipment ratings are typically given in kVA or MVA” [1]

3.3 Reactive power

“Finally, we also specify what we might intuitively think of as the difference between apparent and real power, namely, reactive power. Reactive power is the component of power that oscillates back and forth through the lines, being exchanged between electric and magnetic fields and not getting dissipated. It is denoted by the symbol Q, and its magnitude is given by” [1]

$$Q = I_{RMS} \cdot V_{RMS} \cdot \sin\varphi \quad (7)$$

Again, note how the equation converges for the resistive case where Φ=0 and sin sinΦ=0, as there will be no reactive power at all. Reactive power is measured in VAR (also written Var or VAr), for volt-ampere reactive. We can represent power as a vector in the complex plane: namely, and arrow of length S (apparent power) that makes an angle f with the real axis. This is shown in figure below. The angle Φ is the same as the phase difference between voltage and current.” [1]

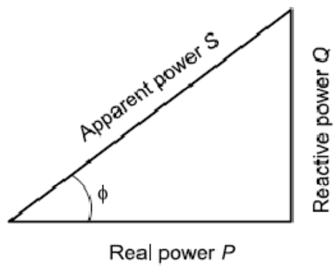


Fig. 3 Power triangle, source [1]

3.4 Receivers and sources of reactive power

It is common, that devices which consume the reactive inductive current are called reactive power receivers, while devices consuming reactive capacitive current are referred to as reactive power sources. [2]

Most of the industrial equipment consumes reactive power. This devices are electric motors, transformers, conductors, chokes, converters, arc furnaces and power electronics.
In random circuit without source, the reactive power is associated with the frequency and the peak value of the energy stored periodically within magnetic and electric field of the elements of the circuit. [2]

The reactive power of inductive and capacitive elements, Q_R and Q_L respectively, can be expressed as:

$$Q_L = UIsin\frac{\pi}{2} = \omega LI^2 = \omega\frac{LI_m^2}{2} = \omega\varepsilon_{mM} \quad (8)$$

$$Q_C = UIsin\left(-\frac{\pi}{2}\right) = -U\omega CU = -\omega\frac{CU_m^2}{2} = \omega\varepsilon_{mE} \quad (9)$$

where ε_{mE} and ε_{mM} are the maximum value of the energy stored in the magnetic field of the inductive elements of the circuit and electric field of the capacitive elements. [2]

Basing on the law of conservation of energy, the input reactive power in the source – less circuit is equal to algebraic sum of reactive power of the inductive and capacitive elements included in a circuit, that is: [2]

$$Q = \sum(Q_L + Q_C) = \omega\sum(\varepsilon_{mM} - \varepsilon_{mE}) \quad (10)$$

Considering any electric circuit, one knows, that the generated reactive energy is equal to the consumed energy. According to this, that most of the loads in the industry are the loads that needs inductive reactive energy to operate. For this reason, the reactive power demand is much more than the generator is able to produce. Therefore, there are a devices that needs to be connected to the system in order to provide an extra source of inductive reactive power or devices which will absorb capacitive power. These type of devices are: capacitor banks, synchronous motors, and power electronic sources of reactive power. The cooperation of compensating devices with linear circuits causes the reactive component of the supplying current to decrease. [2]

3.5 Power – time and frequency domain

There are many of theories about power in electrical circuits, but there are two groups that they are can be divided in. One of them is considering frequency domain while the second one is related to time domains. Before these two approaches are explained, there is a one definition that needs to be introduced, namely, distortion power. One needs to deal with distortion power, when the instantaneous values of the voltage and current at the circuit`s terminals do not fulfill the Ohm`s law. The distortion power can be determined basing on the active and apparent power

$$D^2 = S^2 - P^2 \quad (11)$$

The distortion power of a linear electric circuit is very often referred to us a power of phase shift, because the phase shift between the voltage and current cause this power to appear.

3.5.1 Frequency domain

a) Budenau`s theory

Power theory in the frequency domain was published in 1927 by Budenau. He introduced two equations for the power within nonlinear electric circuits supplied by sinusoidal voltage, with periodical non sinusoidal current waveforms. Budenau defined the reactive power as [2]:

$$Q = \sum_{n=1}^{\infty} U_n I_n sin\varphi_n \quad (12)$$

He also introduced the power component, so called distortion power D, describing it as follows:

$$D^2 = \sqrt{S^2 - P^2 - Q^2} \quad (13)$$

b) Harashim`s theory

Harashim assumed, that the sinusoidal voltage and load current can be expressed by following formulas [2]:

$$u = A \sin \omega t \quad (14)$$

$$\mathrm{i} = \mathrm{B_1 sin\omega t + C_1 cos\omega t} + \sum_{n=2}^{\infty} \mathrm{B_n sin(n\omega t)} + \sum_{n=2}^{\infty} \mathrm{C_n cos(n\omega t)} \quad (15)$$

$$\mathrm{u} = \mathrm{B_1 sin\omega t + C_1 cos\omega t} + \sum_{n=2}^{\infty} \mathrm{B_n sin(n\omega t)} + \sum_{n=2}^{\infty} \mathrm{C_n cos(n\omega t)} \quad (16)$$

The load current contains active and reactive component of fundamental harmonic and a sum of higher order harmonics. The sum can be considered as the component of distortion of the current. The formulas above says, that if the load current value and amplitude of active component are known, one can determine reactive component of load current [2].

$$\mathrm{i_q = i - B_1 sin\omega t} \quad (17)$$

The amplitude of active component of load current can be determined basing on the value of the active power of the load [2]

$$\frac{\omega}{\pi}\int_{\mathbf{0}}^{\frac{\pi}{\omega}} ui\,dt = \frac{\omega}{\pi}\int_{\mathbf{0}}^{\frac{\pi}{\omega}} Asin\omega t\,\left[\sum_{n=1}^{\infty} B_{2n-1}\sin(2n-1)\,\omega t + \sum_{n=1}^{\infty} \mathrm{C}(2n-1)\,\omega t\cos(2n-1)\omega t\right]dt = \left(\frac{A}{2}\right)B_1 \quad (18)$$

The analysis of the active power component was developed by the Nowomiejski and Emanuel.

3.5.2 Time domain.

Fryze`s theory

The Fryze`s theory from 1932 assumes, that apparent power S of an electric circuit contains two components of the power, active component P and reactive component Q, described by the following formulas [2]:

$$S = IU \quad (19)$$

$$P = \frac{1}{T}\int_0^T s(t)dt = \frac{1}{T}\int_0^T u(t)i(t)dt \quad (20)$$

$$Q^2 = S^2 - P^2 \quad (21)$$

According to the theory, everything else than the active power is considered as reactive power, and should be removed from the circuit. Instantaneous current value of the receiver can be shown as a sum of active (ir) and reactive (iq) component of the load current [2]

$$i = i_r + i_q, \quad i_r = \frac{P}{\|u\|^2}\, u, \; i_q = i - i_r \quad (22)$$

4. Power factor and its influence on supplying source

The power factor definition is correlated with sinusoidal current circuits. In the linear AC current circuit supplied by the sinusoidal voltage the power factor is referred to as cosφ, where φ is an angle of phase shift between the sinusoidal waveform of supplying voltage and sinusoidal current waveform, that is [2] [3]:

$$\lambda = cos\varphi = \frac{P}{S} = \frac{U \cdot I \cdot cos\varphi}{U \cdot I} \quad (23)$$

Generally speaking, one can say that power factor of electric circuit says how much of the energy the circuit can get with respect to the electrical efficiency of the supplying source. In other words, if the receiver is able to get all the power flowing from the source, then power factor value is equal to one. Such situation is possible, when the Ohm`s law is fulfilled. The main reason for the power factor value to be smaller than one, is that the electric circuit accumulate certain part of the energy. Moreover, the distortion of the current waveform with respect to the voltage waveforms cause the power factor value to be smaller than one. Virtually, there are many of the circuits which may have both mentioned features, i.e. thyristor controller with the RL load. In such case, the power factor can be expressed as: [3] [2]

$$\lambda = \frac{P}{S} = \frac{\frac{1}{T}\int_0^T u(t)i(t)dt}{\frac{1}{T}\sqrt{\int_0^T u^2(t)dt \int_0^T i^2(t)dt}} \quad (24)$$

In sinusoidal electric circuits which cause a non sinusoidal periodical current to flow, there are two components of the power factor to be considered, that is component correlated with phase shift between the first harmonic of the current and voltage referred to as cosφ. The second component is associated with current waveform distortion with respect to the voltage waveform and is referred to as γ. The phase shift factor and distortion factor is expressed by the formulas below, respectively [2]:

$$cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} \quad (25)$$

$$\gamma = \frac{I_1}{I} = \frac{I_1}{\sqrt{\sum_{k=0}^{\infty} I_k^2}} \quad (26)$$

Where: I_1 – the RMS value of the fundamental harmonic of the current

I – the RMS current value flowing in the circuit

In order to assess what is the higher order harmonic content in sinusoidal current on voltage waveform, the THD (Total harmonic distortion) factor was introduced [2]:

$$THD = \sqrt{\frac{\sum_{n=2}^{\infty} A_n^2}{A_1^2}} \quad (27)$$

Where n denotes the harmonic order, index "1" – fundamental component of the A waveform. The "A" denotes current or voltage,

There is a possibility, to express the harmonic content in the current or voltage waveform by the voltage or current distortion factor given by the following formula:

$$\gamma = \frac{A_1}{A} \quad (28)$$

Where: A_1 – RMS value of fundamental component

A – RMS value of the waveform being analysed

One can notice, that there is a relationship between two formulas above, that is:

$$THD^2 = \left(\frac{1}{\gamma}\right)^2 - 1 \quad (29)$$

One can also determine the individual harmonic distortion factor HD, which is described by the ratio of the "n" order harmonic of waveform A to the fundamental component of this waveform

$$HD = \frac{A_n}{A_1} \quad (30)$$

The HD factor gives more explicit assessment of the influence of the n order harmonic on waveform A. Therefore, the power factor will be given as [2]:

$$\lambda = \frac{P}{S} = \gamma\ cos\varphi = \frac{I_1}{I}\frac{P}{\sqrt{P^2 + Q^2}} = \frac{P}{U\sum_{K=0}^{\infty} I_k^2} \quad (31)$$

The power factor value of the loads that cooperate with the power system affects the voltage conditions of the load operation. Moreover, the degree of utilization of the power generating and transmitting units depends on the power factor value of the loads connected to the network. All the devices that are included in power system has determined the maximum current that can flow through them, causing no malfunctions because of heat. In three phase circuits, for a device with the rated power P, current value can be calculated from [2]:

$$I_n = \frac{P_n}{\sqrt{3}U\lambda} \quad (32)$$

The dependence above says, that for the particular electric device of the rated current In, at the constant voltage level U, the ratio of the nominal power Pn to the power factor is constant. If one decrease power factor value, as a result, the active power flow will be limited, which in turn, decreases the capability of energy transfer of feeders, transformers as well as apparatus that generate the energy [2].

Decrease of power factor value of the load connected to the network, causes the rise of armature impact of the supplying generator. Therefore, one has to deal with voltage drop of the voltage drop that is being generated. In order to counteract the voltage to drop, one needs to increase the excitation. But this solution has also limitations, because of temperature limits of the rotor. That is why, the active power of the load has to be decreased. That is why, the generator`s active power as a function of power factor change decreases much faster that it seems from the formulas given in this subsection. [2]

The improvement of the operation of electric loads is possible, at given rated voltage. The voltage of the electric loads depends strictly on the voltage drops along the feeder. For sinusoidal current, the voltage drop in feeder of resistance R and reactance X is calculated as: [2]

$$\Delta P = RIcos\varphi - XIsin\varphi \quad (33)$$

Especially in high voltage line, where the X/R ratio is more than 1, when $cos\varphi$ decreases, the voltage drop increases. The power losses of transmission line are inversely proportional to the square of power factor at constant value of transmitted active power. Let`s consider the feed with resistance R, and current I flowing through it causing the voltage drop equal to ΔU and active power losses ΔP, where [2]

$$\Delta P = I\Delta \mathrm{U} = \mathrm{I}^2\mathrm{R} \quad (34)$$

For the three phase system

$$P = 3\mathrm{I}^2\mathrm{R} \quad (35)$$

Putting In (32) current value of the electric device to the ΔP equation (36), one can obtain

$$\Delta P = \frac{P^2R}{U^2cos\varphi} \quad (36)$$

It is desirable to notice, that reactive power has the same consequences for the feeder as the active power. The active power losses caused by the electrical device of rated power P and Q connected to the feeder are calculated as: [2]

$$\Delta P = \left(\frac{P^2}{U^2} + \frac{Q^2}{R^2}\right)R \quad (37)$$

The formula above shows, that at the constant value of line resistance, power losses and supplying voltage, the increase in reactive power cause the active power to decrease [2].

4.1 The aim of power factor correction

Nowadays, the power electronic devices being installed almost everywhere. Then UPS system for the computers, fast changing load and etc. make the energy quality worst. In many case, installed inductive load changes the network behaviour for the inductive one. In order to prevent it, certain amount of reactive power ahs to be launched to the mains in order to achieve proper network behaviour. In most cases, the reactive power compensations flows from the economic reason. The industrial plant producing too much reactive power, has get rid of it in some way. When there are no any compensators in the mains, the energy supplier has to get back all the reactive power tha was produced. Therefore, energy suppliers charge a customer in such case. Main aims of the reactive power compensation are [4]:

- Maintaining the tgδ as determined by the energy supplier in order to avoid paying
- The energy consumption becomes cheaper
- Improving power quality
- decreasing power losses
- decreasing the cross section of the wires
- decreasing transformer costs as well as its power losses
- lower voltage drop of supplying network

4.1.1 Power quality – nonlinear loads

There are more and more energy consumers, that use devices with nonlinear current – voltage characteristics, what affects the power quality delivered by the energy supplier. This type of device connected to the network are generating the higher order harmonics, which in turn, are main reason of supplying voltage distortion. The harmonics has been the most disturbing distortion in the electric systems, and the problem still is not solved since the problem is being gained.

The power quality parameters are worst because of:

- nonlinear loads
- electromagnetic immunity of devices on electromagnetic distortions is smaller
- electromagnetic ecology

The main point of the power quality improving is to understand the problem by the energy customers and suppliers. In order the describe the sources of the power distortion, it is necessary to determine which parameters of the power decides about the quality.

4.1.2 Main sources of power distortions

The characteristic thing about the energy, is that its quality strictly depends on the end user. The factors, that affects the power quality the most are: faults in power system, substations mains, as well as switching on and off the loads of the high power. Moreover, installation of the big amount of nonlinear loads such as lighting, electronic devices in the vicinity of the nonlinear, high power electric drive has a negative consequences. We can distinguish three groups of harmonics sources in the power system [5] :

- arc devices such as arc furnace, welding machines etc.
- devices with electromagnetic cores such as transformers, electric motors or generators
- electronic and power electronic devices

The energy consumers are using more electrical devices, which converts the energy. This devices, very often consist of capacitors, filters, rectifiers. The state of the art computers, TV, and lighting also affects the phase currents. The nonlinear loads produce higher order harmonic, especially the 3^{rd} , 5^{th}, 7^{th} etc. The harmonics of the currents cause some problems in the mains while the voltage drop across the line impedance distorts the voltage [5].

4.1.3 Influence of the non linear loads on the power quality parameters

The nonlinear loads having electronic inputs, converts the delivered energy into the same type of energy, but with different parameters than the one in the feeder. This type of power conversion allows to control the conversion of the energy in order to obtain the other type of energy, i.e. the mechanical one. It concerns the electric motors, lighting and heating. All the energy saving systems basing on the semi-conductors (diodes, thyristors etc.) allows for the energy savings, bu on the other hand they launch distortions to the electric grid. The nonlinear loads are being used more often in many locations. In the ideal supplying system, the current and voltage waveform is strictly sinusoidal. In case, where there are the nonlinear loads in the system the waveforms are distorted. As a result of the nonlinear loads, one may have a problem with the increase of the RMS current of the capacitors for the reactive power compensation. The devices that are prone to the harmonics are, among other things, transformers. The harmonic presence makes the power losses of the transformer core bigger. Distorted currents may cause [5]:

- higher supplying power
- higher power losses of transmission line
- malfunction of protection
- overheating of transformers and motors
- malfunction of capacitors for reactive power compensation
- increase of the current in neutral conductor
- disturbances for sensitive devices

  shorter life expectancy of the insulation

5. Reactive power compensation methods.

Generally speaking, a undesired power factor value caused by inductive load connected to the supplying network can be corrected (compensated) by means of loads having capacitive behaviour. Practically, there are two methods of reactive power compensation in electric networks, which are depicted on the diagram below:

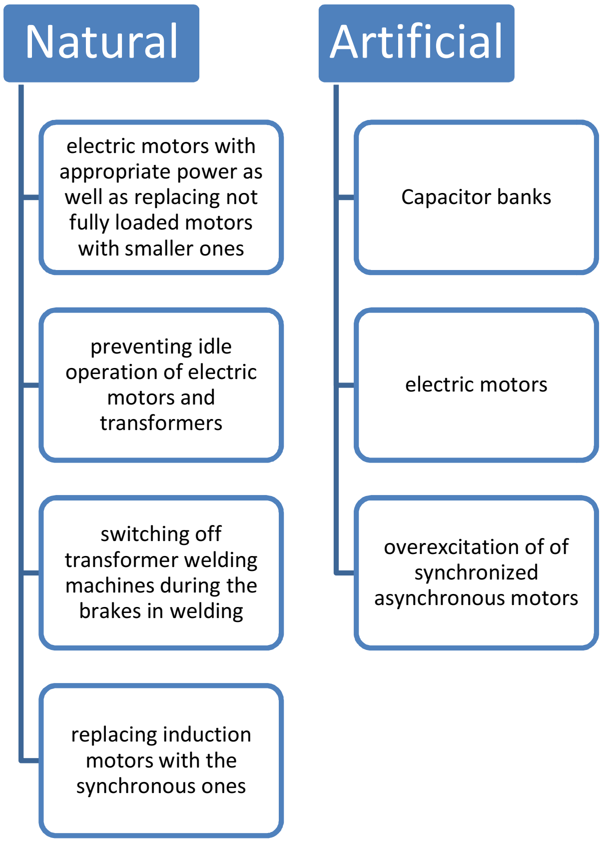


Fig. 4 Devices for natural and artificial compensation method, source [4]

For not complex electric grids where there is a small amount of inductive loads, natural method of compensation might be good enough, especially when desired parameters of the grid are not excessive. In case of large power grids, mentioned method is not sufficient, so there is a need to improve the network parameters by means of artificial reactive power compensation method. [4]

5.1 Single, group and bulk power factor correction

There are few possible configurations of compensating systems, however there are three basic methods that can be distinguished: [6]

- **Single (fixed) power factor correction –** put in practice by connecting power capacitor directly to terminals of a device that has to be compensated. Thanks of this solution, electric grid load is minimized, since reactive power is generated at the device terminals. This method eliminates controlling devices, since capacitor is being switched on and off by means of the same switch as the device. The main disadvantage of this method, is that the capacitor is not being used when the device is not operating. Moreover, the series of type of capacitors offered by manufacturers is not always sufficient to meet the requirements.

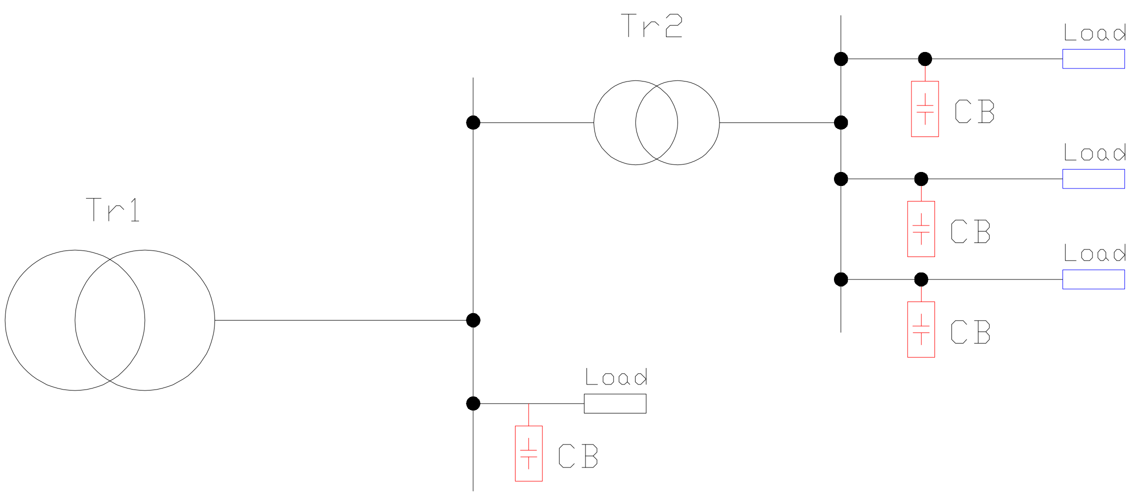


Fig. 5 Illustration of fixed power factor correction

The figure above depicts capacitor banks connection (CB) in an example electric system. It is noticeable, that each CB is connected directly to a particular load.

- **Group power factor correction –** this method is more effective than the previous one. Group PFC assumes compensation of a group of loads supplied by the same switchgear. Capacitor bank is usually controlled by the microprocessor based device called power factor regulator. Beside, this method force applying protection for power capacitors.

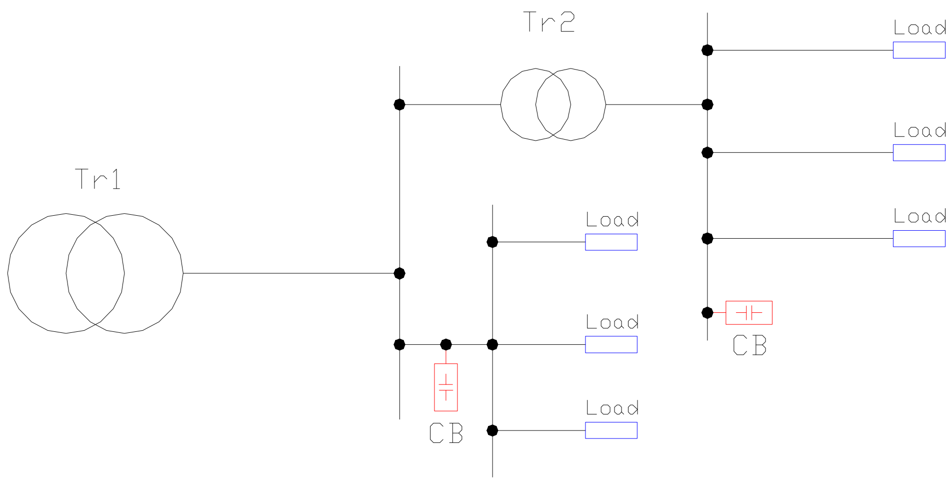


Fig. 6 Illustration of group power factor correction

In this case, capacitor banks are connected to the bus-bars, which supply a group of loads.

- **Bulk compensation –** this method assumes one compensating device for the whole object (inside the transformer station or in switching station). This solution minimize total reactive power to be installed and power factor can be maintained at the same level with the use of automatic regulation what makes the PF close to the desired one. The drawback is that supplying and distribution network, transformer as well as mains supplying all the equipment is loaded by reactive current.

  This type of compensation method demands capacitor banks to have wide range of power regulation, which can be determined by 24h measurements at the place of CB installation. This is not the best solution for large electric system, especially when the distance between the source and nonlinear receivers is long. The longer distance, the bigger losses in transmission system. For this reason most commonly used method of PFC is the group compensation, while for nonlinear loads of big power single compensation is applied. [4] [6]

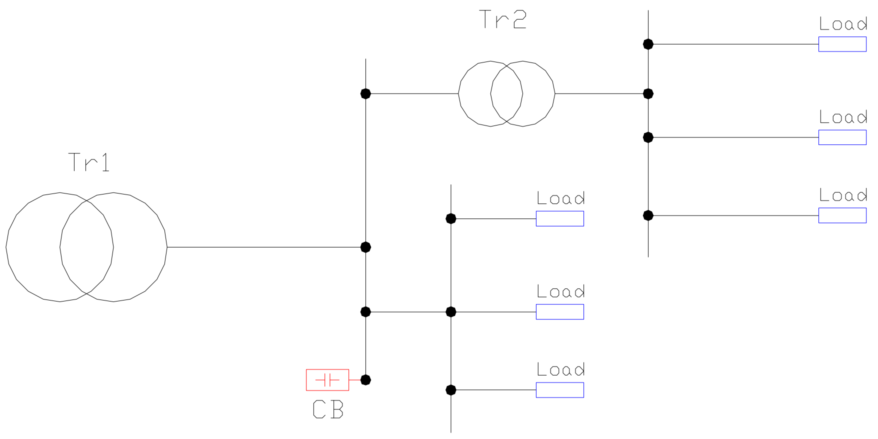


Fig. 7 Illustration of bulk power factor correction

In the matter of fact, each method can be applied for reactive power compensation in power grid, but each with different effectiveness. In order to put in practice particular method, it is necessary to fulfill some conditions. The factors that decides about the choice of satisfying methods are as follows[3] [4] [6]:

- Number of receivers in a grid and how many of them needs PFC
- Demanded level of grid compensation
- Size and grid complexity
- Possibility of CB arrangement
- Type of equipment connected to the compensated mains and its behaviour (inductive/capacitive)
- Higher order harmonic presence

Sometimes, depending on the factors listed above, more than one method has to be applied in order to meet the PFC requirements [3] [4].

5.2 Advantages and disadvantages of the methods of PFC

Once all PFC methods were discussed in previous section, one can focus on advantages and drawbacks of each one.

Tab. 1 Advantages and disadvantages of PFC methods

PFC Method	Advantages	Disadvantages
Fixed	- Compensation at the place of reactive power generation. - Minimize the load at the mains - Small capacitor power - No regulator for control , multi-level CB	- Maintains demanded tgφ only for one piece of equipment - Switching the device off stops operation of capacitor bank - Big amount of compensating units - Does not compensate whole grid
Group	- Minimized number of capacitor banks compared to single compensation method - Particular parts of the mains are being compensated (closer to the source)	- poor adaptation to the mains parameters - very often needs controlling devices (PFR) - more expensive than bulk compensation in terms of the bigger number of capacitor banks
Bulk	- The cheapest method - Limited number of capacitor banks	- Ensure constant gφ value only at the terminals - Mains inside an object is not sufficiently compensated - Risk of distortions and resonance phenomenon occurrence
Motor compensation	- No additional distortions - Effective compensation method	- The most expensive method of compensation - Energy losses for overexcitation of synchronous and synchronized. - Shorter life expectancy of electric motor - Grid is not fully compensated

6. Devices for reactive power compensation

In the most cases, PFC is used for economic reasons. Using compensating device, one can save on electricity bill as well as keep certain grid parameters determined by the energy provider. Power factor correction gives even more profits, than only savings. Compensating "unnecessary" reactive power the current carrying capacity of an existing network can be sufficient to sent more active power through it, maintaining the same ratings of the apparatus within the supplying and distribution system. PFC also allows to decrease transmission losses and limits voltage drops. Generally, reliability of the network gets better. But one should be aware, that compensating device connected to the mains, can also have negative consequences like:

- Transient generation
- Higher order harmonics generation
- Long lasting voltage rise
- Gain of higher order harmonics
- Voltage drops, outages and Overvoltage of short duration
- Other kind of distortions

All of this can be caused for few reasons, such as resonance phenomenon, mistakes in design, use of unsuitable equipment, wrong exploitation. But despite of all negative consequences, there are also positive ones, which will definitely improve energy quality. These are as follows:

- Limitation of reactive power
- Adjustment of a voltage at receivers (burden) terminals
- Higher order harmonic filtration
- Phase voltage symmetrisation
- Limitation of voltage swing and flickering

Bearing above in mind, before one decides, what kind of compensating device will be used in particular case, there is a few factors and conditions that has to be taken under consideration, such as [4]:

- Rating of the mains, that is : voltage, frequency, and it`s real value (measurement)
- Demand on inductive reactive power taking into account the aim of compensation
- Dynamics of load
- Presence of higher order harmonics of a current and voltage
- Short circuit parameters at the capacitor bank future location
- Ambient conditions
- Place of installation

Compensating devices can be classified into four groups:

- Power capacitor based compensators
- Power electronics compensators and active filters
- Hybrid compensation systems (power capacitors and power electronics based)
- Synchronous machines

6.1 Power capacitor based compensating devices

Power factor correction method based on power capacitors is the biggest group of the devices used in the industry and by the private users, mainly from economic reasons. On the other hand, they may be a reason of unwanted distortions at the spot of operation. That is why they should be carefully selected, in accordance with actual standards.

In terms of rated voltage of capacitors we can distinguish two groups of capacitor banks:

- Low voltage ($U_n \leq 1000V$)
- High voltage ($U_n \geq 1000V$)

6.1.1 Low voltage capacitor banks

There are many manufacturers on the market offering devices for reactive power compensation. The most commonly used ones are capacitor based banks. Static compensation using single capacitor unit is utilized mostly for compensation of idle losses of electrical motors and transformers. In order to match appropriate CB to a mains parameters, the apparent power of harmonic source (S_n) and transformer (S_T) has to be known. Then, depending on its ratio, that is $\frac{S_n}{S_T}$ expressed in percent, it is possible to classify capacitor banks in following way [7]:

a) Standard capacitor banks → $\frac{S_n}{S_T} \leq 15\%$

   the rating of the elements of the CB are the same as the rated voltage of supplying network.

b) Overrated capacitor banks → $15\% < \frac{S_n}{S_T} \leq 25\%$

   The power capacitors have higher rated voltage than the rated voltage of the mains where CB is to be installed. This type of CB are not equipped with reactors

c) Detuned capacitor banks → $25\% < \frac{S_n}{S_T} \leq 60\%$

   This type of CB are equipped with reactors and overrated capacitors connected in series (acceptor circuit). They can be used in the mains, where higher order harmonics are present.

If the ratio of $\frac{S_n}{S_T} \geq 60\%$, it is demanded to use harmonic filtering together with capacitor bank. The filters have to be tuned to particular harmonic or group of harmonics.

The photographs below shows an example configuration of LW capacitor bank.

Fig. 8 Capacitor bank by Twelve Electric, source [8]

Fig. 9 Capacitor bank by Twelve Electric, source [8]

6.1.2 Standard capacitor bank design

The standard capacitor bank consist of following segments [6] [9] [4]:

- Supplying element – this ensures connection to the electric network
- Capacitors section – consists of capacitor, switching apparatus and capacitor unit protection
- Control circuit – this circuit measures actual power factor and make decision whether connect the capacitors or not
- Barrier - mainly for maintenance crew safety. Separates electrical circuit being under the voltage as well as protects from getting foreign matter into the CB.

Electrical circuit of the capacitor bank can be divided into two groups:

- Main current circuit
- Control circuit

Main current circuit is responsible for electric energy transfer while control is responsible for measuring and decision making. Usually, in case of detuned capacitor banks, there is a rule that assumes one common detuning factor for each stage of the CP. In the opposite case, there is a risk of overload.

6.1.3 Capacitor bank equipment

Switching equipment as well as short circuit protection of capacitors should be selected so that they can easily handle the capacitor rated current. Moreover, they should be able to withstand 1.3 x rated current flowing through the capacitor. Usually, the capacity deviation of the power capacitors can be up to $\pm 10\%$ of rated value. Therefore, current flowing through the capacitor can reach higher value, that is $1{,}3 \cdot 1{,}1 = 1{,}43$ times the rated current of capacitor unit. Furthermore, switching operation can cause over-currents of high frequency. For this reason all the apparatus used in the capacitor bank has to be suitable for such conditions [3].

The table below presents the most common low and high voltage capacitor bank equipment:[poradnik]

Tab. 2 Low voltage capacitor bank equipment

Voltage level	Capacitors	Switching apparatus	Protection	Automation
Low voltage	The most commonly used are delta connected (internally) three phase capacitors	Contactors specially designed for capacitors with additional module for switching surge limitation	Fuses, switch disconnector, fuse protection of control circuit	Reactive power factor regulator
High Voltage	One phase with one or two insulators Three phase, usually star connected (internally), sometimes delta connected	Vacuum contactor or SF_6 Disconnector i.e vacuum one Switches	HV fuses Relays and overcurrent or overvoltage release cooperating with disconnectors	Reactive power regulator Electromagnetic lock

Summing up, the capacitor bank unit design should be safe for maintenance crew, apparatus rating should consider all the overvoltages and overcurrents that may occur during switching operations. The elements arrangement inside an enclosure should be well thought. All the equipment have to be easily available for replacement in case of failure.

6.1.4 Capacitor bank protection

Proper operation of capacitor bank is very important issue. One needs to bear in mind, that capacitor bank switching can cause many unwanted phenomena. According to the standards, the capacitor bank can be disconnected when [6] [9] [3]:

- Increased voltage across capacitor bank terminals. In some cases, increased voltage is permissible as far as it does not exceed 110% of rated voltage
- Current value is greater than 130% of rated current of capacitor bank
- phase currents asymmetry no more than 5% for star and 10% for delta connection, referring to the phase current in the phase that is the most loaded
- ambient temperature is higher than the one determined in the technical documentation
- capacitor deformation
- sparking on capacitors` terminals and other issues that may cause the problems during operation

Types of protection

In the capacitor banks, there are plenty of distortions that may occur such as voltage rise, short circuits, interior capacitor failure, rise of temperature, and others. In order to protect the capacitors, there is a need to apply additional protection. In the below section of this work, the typical distortion are described as well as the method to protect from them [6] [9] [3].

a) Increase of supplying voltage may cause rise of reactive power produced by a capacitor according to the formula

$$Q_C = U^2 \cdot \omega C \quad (38)$$

In result, there is a risk of the temperature rise of the unit. In order to protect against this type of distortion, overvoltage relay (for voltage control) and overcurrent protection (for phase current control) might be used.

b) Phase to phase fault can cause exterior fault. The protection is easily feasible through instantaneous overcurrent protection. The protection setting should be as follows:

$$I_P = (1{,}5 - 2)I_N \quad (39)$$

With operation time below 0.3 seconds

c) Damages within capacitor bank can be caused by the faults within the unit. Usually, star – delta overvoltage relay is used to prevent a failure, supplied by open-delta voltage transformers. The second solution is overcurrent star – star relay connected to neutral points of star connection of both units

d) Temperature rise can bring the same effect as described in the point “a”. In order to prevent this type of failure two level temperature sensors are being used. The sensor has to send information that is able to do both, signalize overheating and disconnect the unit.

e) Distortions in form of failure or overload which can be cleared by delayed and instantaneous fuse – link.

6.1.5 Connection of a capacitor bank to the electric grid.

Usually, capacitor banks are connected to the three phase electric networks. Power factor regulators, depending on the design, can be supplied by 230V or other voltage. However, most of them needs 230V of the supplying voltage. In order to achieve that, one can use a 400 / 230V transformer. Power factor regulator needs to be connected to the one phase by the current transformer using small cross section wire, such as i.e. YDY 2 x 2,5mm^2. The current transformer secondary site rated value is to be 5A. The primary site rated current depends on the mains the capacitor bank is going to operate with. Assuming three phase mains, with phase marking L1, L2 L3, and current transformer on the phase L1, the two other phases have to be also connected to the power factor regulator as the voltage measurement circuit. One needs to bear in mind, that phase that is being used by the CT cannot be connected to the mentioned measurement circuit!

Each stage of capacitor bank is connected to the supply through the main current circuit. The current circuit is made of cooper bus bars which cross section is carefully selected taking into account total reactive power of the capacitor bank as well as the supplying voltage. Summing up, the cross section of the bus bars within the CB are dependent on the total reactive current flowing through the main current circuit. Furthermore, each section of the CB is equipped with short – circuit protection and contactor.

It is important, to ground all the elements, that might be touched by the human. For the personnel safety, there should be an additional master switch, which allows to disconnect the capacitor bank from the main supply for maintenance without switching it off in the supplying switchgear. The drawing below depicts the principle of capacitor bank connection to the three phase electric network through the current transformer. Numenclature for the picture

Tr1 – supplying transformer, CT – current transformer, MS – master switch, PFR – power factor regulator, F – fuse, C – capacitor, Cont - contactor

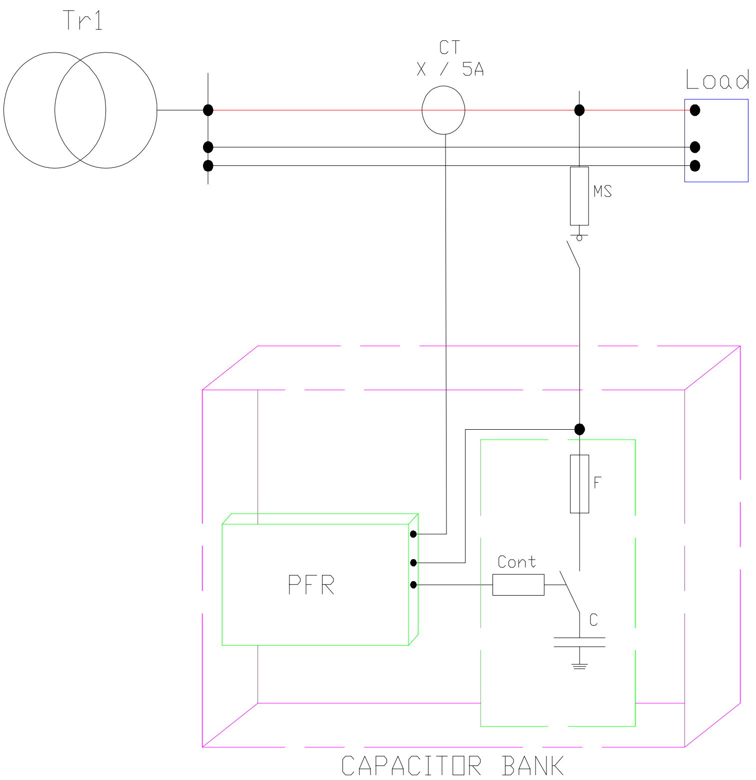


Fig. 10 Capacitor bank to network – connection scheme

6.1.6 Classification of capacitor based compensation equipment

- Supplying voltage [4]
  - Low Voltage: up to 1kV
  - Medium Voltage: up to 30kV
  - High Voltage: above 110 kV
  - The highest voltage: above 110kV
- Frequency
  - frequency of supplying network (50Hz or 60Hz)
  - higher than network frequency (i.e. induction furnaces)
- Phase Number
  - monophase
  - multiphase
- Control Method
  - Manual
  - switching by hand
  - automatically switched
  - auto - controlled
- Protection against higher Order Harmonics
  - without reactors
  - detuned filters
  - passive filters of higher order harmonics
- Environmental conditions
  - Overhead
  - Internal
  - External
- Special environmental conditions
  - very high/low temperature, high humidity
  - mains
  - dust
  - chemicals

6.1.7 High voltage capacitor banks

In the mains, where the rated voltage is higher than 1kV, the connection scheme of the capacitor units depends upon their rated voltage as well as a transformer neutral point to ground connection scheme. Three phase units are being used for fixed compensation. These capacitors have not got any leads of neutral point although the windings are interlay WYE connected. In order to make it possible to achieve an external connection to the neutral point, single – phase capacitors are being used by connecting them in WYE scheme. The important feature is that the capacitor banks and filters accuracy depends on their parameters constancy during normal operation. The parameters that can be changed is i.e. the capacitor bank capacity. It might be caused by the local breakdowns that will trip and disconnects affected windings of the capacitor. In order to monitor the capacitor bank parameters (detection of capacitance change caused by internal faults) each compensating or filtrating stage is divided into two equal sections (two star YY) . Then, the equalizing current between neutral points of the two sections can be controlled. High voltage capacitors with one insulator are used in mains with isolated neutral point. They also should be well-isolated from the ground by putting the capacitors on the isolators [10].

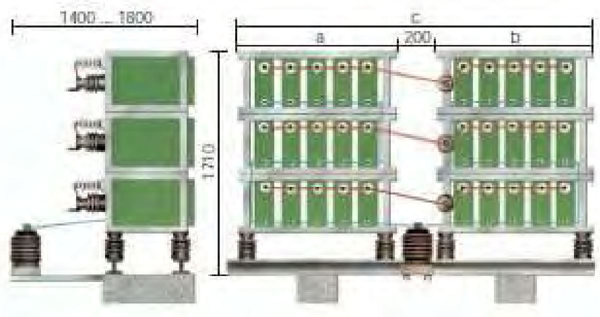


Fig. 11 Static capacitor bank 9,09kV and 200kVar rated power by Zez Silko, source [10]

Fig. 12 Enclosed capacitor bank source [10]

The capacitor units has two terminals isolated from its body can be also delta – connected, but this solution is not being used very often. Star connected capacitors operates at the phase voltage, which is $\sqrt{3}$ times lower than in case of delta connection. In terms of the limited voltage range of high voltage capacitors they are often series connected in the mains with the highest voltage. High voltage capacitors bank are manufactured as enclosed and overhead ones. Generally, they are being design for the particular industrial plant, power station, etc. and specially prepared depending on the place of installation.

6.2 Synchronous electric motors

Next group of the devices, that might be used for reactive power compensation are synchronous electric motors. They are good alternative for compensation because [3]:

- synchronous motor can produce the capacitive or inductive reactive power continuously

- small cost, including only the costs of the control equipment

For compensation of reactive power are installed motors can be used. However, the best results can be obtained by the means of: [3]

- Motors operating with no constant load, especially when they are underloaded for a long period of time

  Motors with rated power much greater than the active power load i.e. overmotoring on purpose in terms of the destination as reactive power compensators

There are few factors that may decide whether the compensation will be effective or now, namely [3]:

- Dynamic and static compensation capability of the motor
- The method of motor selection and precision with designing of excitation circuit
- Structure and algorithm of the reactive power regulation of one motor or groups of motors

The calculations of synchronous motor parameters for reactive power compensation is relatively difficult, and needs a lot of calculation as well as experienced designers.

This type of compensation is considered as the most expensive one. Moreover, the electrical motors cannot improve the energy quality at the place of compensation, even if they do not generate distortions to the supplying network. That is why, looking for the economical way for the power factor correction, the most common solution is to use the capacitor banks.

6.3 Active filters

Active filters are very good alternative for power quality improvement and power factor correction. They are not being used to often, because of they price. “Filters are devices that accomplish various objectives” [11] [12]:

- to eliminate harmonics
- to reduce high frequency signal
- reactive power compensation in networks polluted with harmonics avoiding resonance

“Furthermore, depending on the type of device used, the currents in an unbalanced, and the neutral line conductors can be discharged.. There are many of benefits from using the filters, among other things, “filter reduces technical and hidden economical costs of an installation”.

The technical cost reduction or technical optimization of the installation is achieved by:

- increase capability of the distribution lines
- Discharges transformers
- Reduces losses and heating in lines and electrical machinery

"When a filter is installed, the true RMS current value is reduced, what gives the higher capability of transformer, and "reduces the harmonic overload factor, so that, reduces the apparent power throughout the installation."

The mentioned hidden cost reduction can be thought as improving productivity by reducing stoppages and breakdowns. Moreover, it assures that there is no installation extension, because its capacity is sufficient.

6.3.1 Active full-flow filters

This type of filtration increases the equivalent impedance of the source for particular harmonics. This type of filter is able to correct both, current harmonics absorbed by the load as well as the distorted voltage present in the system. The impedance of an active full-flow filter is adjusted be means of special power electronic device. If the voltage of the supplying source generates higher order harmonics, they can be eliminated by the filter connected as depicted in the figure below

Fig. 13 Bloc diagram of active filter connection

The active filter produces voltage being opposite in phase referring to the unwanted harmonic component. The filters improve the efficiency of the parallel filter connected across the non-linear load`s terminals [12].

The impedance of active filter should be:

- Close to zero for fundamental harmonic component
- Very high for the harmonic being filtered by the passive parallel filter. It will cause the current to flow through the filter eliminating it from the network [12].

6.3.2 Hybrid filters:

This type of solution is obtained by connecting the active and passive filters. The can be connected either in series or parallel. In such a structure, the passive filter is filtering out the harmonics of i.e. 5th order while the active filter is dealing with the harmonics of other orders.

Connection of the filters to the network:

Active filters may be installed in various places of distribution system

- Centrally , at the main switchgear of particular system, in order to correct harmonics of current in the whole network
- Close to the loads generating harmonics, in order to provide local harmonic filtration

7. LC Passive filters and resonance phenomenon.

7.1 Resonance phenomenon

Resonance in electrical circuit containing inductive and capacitive elements can be thought as the phase difference of voltage and current at the input of the circuit is equal zero for resonance frequency ω_0. One can distinguish two types of resonance: voltage resonance (series resonance) and current resonance (parallel resonance) [2]

7.1.1 Series resonance

The resonance phenomenon is present, if they are capacitive and inductive elements in the circuit connected in series.

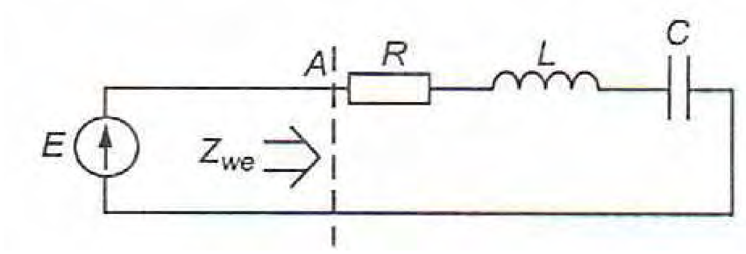


Fig. 14 Schematic diagram of series resonance circuit, source: [2]

The basic formulas for the series resonance are as follows:

- Resonance pulsation: $\omega_0 = \frac{1}{\sqrt{LC}}$
- Wave impedance: $\rho = \sqrt{LC}$
- Quality factor: $Q = \frac{\rho}{R}$
- Attenuation: $D = \frac{R}{\rho} = \frac{1}{Q}$

In the circuit illustrated above, the pulsation ω_L at which the voltage across the coil is maximal, is greater than the resonance pulsation ω_0. Furthermore, pulsation $\omega_C$at the maximum voltage at capacitor terminals is, in turn, smaller than ω_0. The deviation of ω_C and ω_L with respect to ω_0 depends on quality factor, what illustrates the figure below [2]:

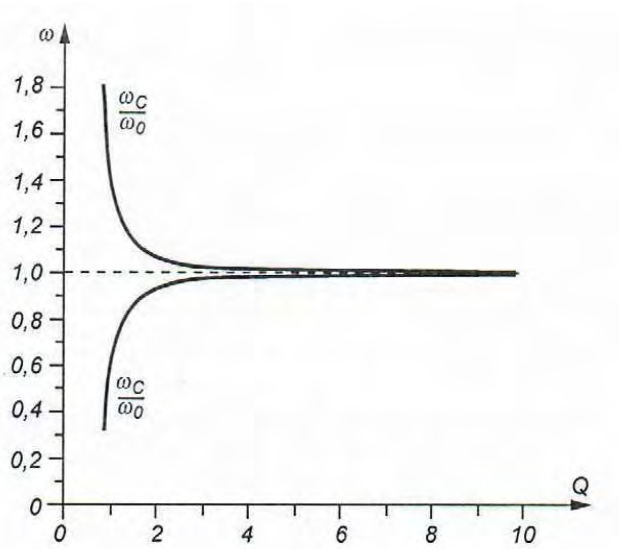


Fig. 15 Dependence of ω_C and ω_L on quality factor Q, source: [2]

If the Q is in range of 5 – 8, then the deviation can be neglected. The maximal current of the series resonance circuit occurs at the pulsation $\omega = \omega_0$ and depends only on resistance value. This type of resonance is dangerous for the network with voltage source. Currents source has a big internal resistance (Q=0) so there is no uncontrolled rise of current [2].

7.1.2 Parallel resonance

Current resonance phenomenon occurs in the circuit where there is a branch of capacitive and inductive elements connected in parallel.

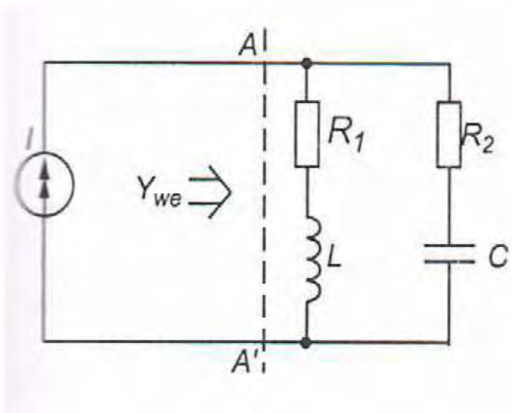


Fig. 16 Schematic diagram of parallel resonance circuit, source: [2]

For the circuit depicted above, the resonance pulsation $\omega_{0R}$is different then theresonance pulsation of lossless circuit, which is equal $\omega_0 = \frac{1}{\sqrt{LC}}$. If $R_1 \neq 0$ and $R_2 \neq 0$, then the pulsation can be expressed as:

$$\omega_{0R} = \omega_0 \sqrt{\frac{1-\left(\frac{R_1}{\rho}\right)^2}{1-\left(\frac{R_2}{\rho}\right)^2}} \quad (40)$$

, where $\rho = \sqrt{LC}$. In this case, the quality factor Q is defined as the ratio of reactance current at the branch at resonance frequency $\omega_{0R}$to the input current. Therefore, the Q can be given by the following formula:

$$Q = \frac{\rho}{R_1 \frac{\omega_0}{\omega_{0R}} + R_2 \frac{\omega_{0R}}{\omega_0}} \quad (41)$$

Usually, in practice, the $R_2 \approx 0$. Then, according to the formulas below, pulsation ω_L(at which the current flowing throughout the inductance reaches maximum value), pulsation ω_C(at which the current flowing throughout the capacitance reaches maximum value) and pulsation ω_{mU} (at which the voltage across circuit terminals is maximal), and $\omega_{0R}$are different then the ω_0

The basic formulas for the parallel resonance are as follows:

- Resonance pulsation: $\omega_0 = \frac{1}{\sqrt{LC}}$
- Wave impedance: $\rho = \sqrt{LC}$
- Quality factor: $Q = \sqrt{\left(\frac{\rho}{R_1}\right)^2 - 1}$
- Attenuation: $D = \frac{1}{Q}$
- The real resonance pulsation $\omega_{0R} = \omega_0\sqrt{1 - \left(\frac{R_1}{\rho}\right)^2} = \omega_0\sqrt{\frac{Q^2}{(1+Q^2)}}$

The graph illustrates the change of $\frac{\omega_L}{\omega_0}$, $\frac{\omega_C}{\omega_0}$, and $\frac{\omega_{Um,}}{\omega_0}$ $\frac{\omega_{0R}}{\omega_0}$ in the function or quality factor Q. At the quality factor in range for Q> 6 – 8 deviation of the ω_L, ω_C, ω_{Um}, $\omega_{0R}$from the $\omega_0$are very small, and can be neglected. That is one can assume, that maximum values of the current and the voltage across the resonance circuit terminals occurs at the resonance pulsation ω_0

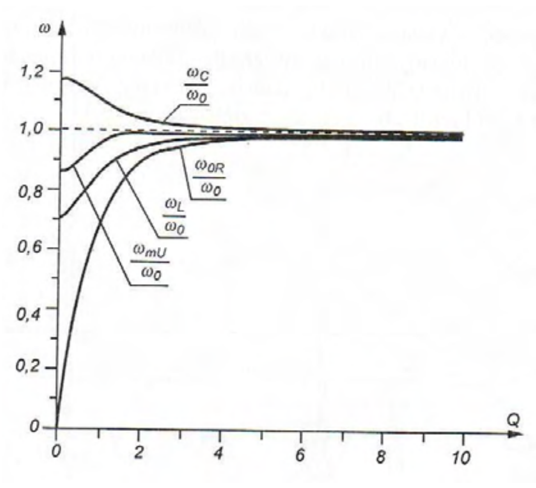


Fig. 17 18 Dependence of ω_C and ω_L on quality factor Q, source

The currents flowing through the circuit as well as the voltage across the terminal are big only, when the circuit is supplied from the voltage source. This type of source is present in the network at the currents produced by the nonlinear loads.

7.2 Passive filters. Harmonic filtering and reactive power compensation

Most of the capacitors banks is equipped with detuning reactors, because of the harmonics present in the supplying network. Because impedance of the capacitors is inversely proportional to the change of frequency, it can be relatively small for the higher order harmonics. That is why there is a need to apply so called detuned reactors. It means, that there is a reactor connected in the series with the capacitor for reactive power compensation. Such a LC series branch for the basic frequency of the supplying network behaves like a capacitor, while for higher order harmonics its impedance is much higher, so that there is no possibility for the big current to flow, which may cause the malfunctions of the capacitor bank elements. The harmonic elimination and reactive power compensation very often comes together. The resonance frequency of the circuit is set for the non harmonic frequency. Otherwise, the compensator could be overloaded. [12]

The reactors parameters are given in percent of the nominal power of the capacitor at 50 or 60Hz (for America). For example, detuning factor of 5% means, that 1/20 of the voltage (at 50Hz) is dedicated for the induction, while 21/21 for the capacitor. If one takes minus it will achieve 100% of voltage. The situation will be the other way around i.e. when f=1050Hz (then voltage at the reactor will be 21/20, while at the capacitor 1/20)

The resonance frequency can be calculated from the formula:

$$p\% = \left(\frac{f_N}{f_R}\right)^2 \cdot 100\% \quad (42)$$

LC circuit is connected to the network in parallel. It can conduct also the harmonics flowing from the other sources then the ones the filter was designed for. If there are no other filters, they might be a need to overrate the filter which will let avoid overload as well as improve the filtering effectiveness. The passive filters are being designed for the particular harmonic. It is detuned for the resonance frequencies i.e. 150 [Hz], (then the reactor reactance is 5%) or 250Hz (then the reactance of the reactor is 4%). Such a filter can handle the 3rd and 5th harmonic with any amplitude even at the overload. That is why this filter should have safety margin [12].

For each frequency, there is few pairs of LC circuits with the same resonance frequency. The capacitance says, how much of the reactive power can be compensated. Then the only parameter to be determined is the inductance, which will, in turns, determines the behavior of the LC circuit for the harmonic frequency. [12]

8. The elements of standard capacitor bank

8.1 Power capacitors

Power capacitors have been used for over one hundred years, since the first alternating current three phase electric grids appeared. From the electrical point of view, they have the same destination and application, the only thing that have changed are the technology of manufacturing and as a result, the efficiency. They are also more ecological than before. Development of technology aspires to minimize the capacitor`s dimensions, active power loses as well as to reach the more power of single unit. Moreover, the manufacturers want to extend the life expectancy of power capacitor to maximum, in order to prevent they replacement. For comparison, the capacitor unit in 70s with the rated power of 20kVar and rated voltage 380\V was 485 high and 350mm wide, and a weight of 26kg, whereas the state of the art capacitor with the same rating weights about 2.5kg. The low voltage capacitor consist of capacitive elements placed within an enclosure. The leads are brought out and connected to the terminals that are insulated from the housing as well as from each other. [13]

8.1.1 Low voltage MKV capacitors

The capacitors used to be made of few layers of special type of paper impregnated in synthetic or mineral oil, and thin aluminum film as a capacitor plates. Nowadays, a little bit different technologies of capacitors manufacturing are being used. [13]

Design

“The winding element of the MKV capacitor consists of a dielectric of polypropylene film and an electrode of double-sided metalized paper. This winding construction achieves low losses and a high pulse-current withstand capability. Oil is used for impregnation of the capacitor. [14]

Contacting

“The end faces of the windings are contacted by metal spraying to ensure a reliable and low inductance connection between the leads and layers. The leads are welded or soldered to these end faces, brought out through insulating elements (ceramic or plastic) and soldered to the terminals.” [14]

Impregnation

“All hollows between the windings and between the windings and the case are filled with an impregnating agent. Besides increasing dielectric strength, this improves heat dissipation from inside a capacitor. The impregnating agents that we use are free of PCB and halogens. They consist of mineral oil, or pure synthetic hydrocarbons that partly contain small quantities of conventional additives (stabilizers)” [14]

Self - healing

“All MKV capacitors are self-healing, i. e. voltage breakdowns heal in a matter of microseconds and hence do not produce a short circuit. Breakdowns can occur under heavy electrical load as a result of weaknesses or pores in the dielectric. The integrity of self-healing capacitors is not affected by such breakdowns. When a breakdown occurs, the dielectric in a breakdown channel is broken down into its atomic components by the electric arc that forms between the electrodes. At the high temperatures of as much as 6000 K, a plasma is created that explodes out of the channel region and pushes the dielectric layers apart. The actual self-healing process starts with the continuation of the electric arc in the propagating plasma. Here the metal layers are removed from the metal edges by evaporation. Insulation areas are formed. The rapid expansion of the plasma beyond the areas of insulation and its cooling in the areas of less field strength allow the discharge to extinguish after a few microseconds. The area of insulation that is created is highly resistive and voltage-proof for all operating requirements of the capacitor. The self-healing breakdown is limited in current and so it does not represent a short circuit. The self-healing process is so brief and low in energy that the capacitor also remains fully functional during the breakdown”. [14]

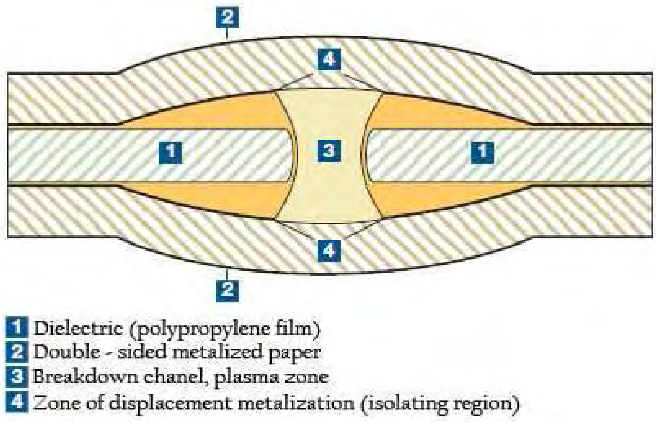
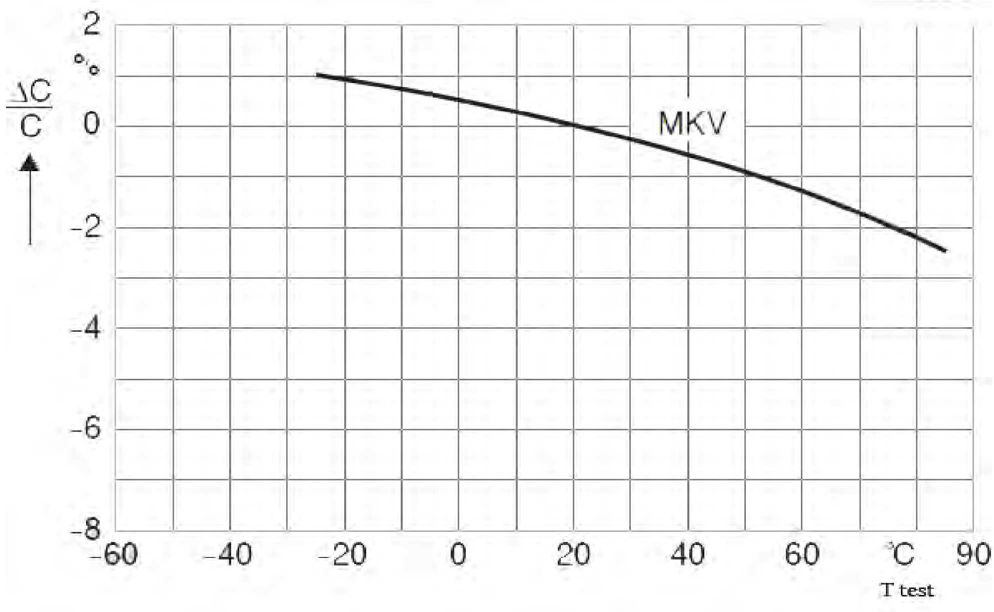


Fig. 19 Capacitor self-healing mechanism

Capacitance

Since capacitors in MKV technology operates mostly in enclosed capacitor banks, their temperature dependence has to be taken into account during designing. Usually, “rated capacitance is referred to a test temperature of 20°C and a measuring frequency range of 50Hz to 120Hz”. Capacitors of MKV type has to have determined the capacitance tolerance range “within which the actual capacitance may differ from rated capacitance. The actual capacitance is to be measured at temperature of 20°C”. “ The capacitance variation in the permissible temperature range is not linear, but is reversible. The figure below dhows the characteristic change in capacitance ΔC/C as a function of test temperature. [14] [13]



T test

Fig. 20 Relative capacitance change ΔC/C versus test temperature Ttest

Capacitance is subject to irreversible in addition to reversible changes, i. e. capacitance drift, the sum of all time dependent, irreversible changes of capacitance during service life. This variation is stated in percent of the value at delivery. The typical figure is +1/– 3%. [14]

Enclosure

There are two shapes of enclosure of low voltage capacitors:

- Cubical
- Tubular

Fig. 21 Shapes of power capacitors [8]

Up to the early 80`s there was almost only capacitors units in steel tubular enclosures. Although the state – of – the art capacitors differs from the old ones, the cubical shape is still being used because it’s easier to installation, takes not that much space as the tubular ones as well as the old units can be replaced with new ones of the same shape. [13]

Configuration

The capacitor units in cubical enclosures may be a three or one phase capacitors. In practice, the cubical units can have rated power of one capacitor up to 100kVar. However, the tubular capacitors has to be classified as follows [13] [14]:

- low voltage power capacitors, with the rated power up to 4,17kVar. These type of units might be used for designing a capacitor of greater rated power. Then, the proper number of capacitors is closed in cubical enclosure. This type of solution is very convenient in terms of the maintenance and money – saving. Let us consider a situation, were there is a unit consisting of “n” capacitors of small power. Probability, that all the capacitors will broke down at the same time is very small. Therefore, even if one of the capacitor closed in the unit will broken down, the rest of them can operate as before.
- Low power one phase capacitors, up to 50kVar for special applications
- High power capacitors units, very often used for the reactive power compensation

Rated voltage and frequency

Low voltage power capacitors are manufactured for the phase – to - phase voltage in the range of 230 up to 1000V. The most frequently used voltages of the capacitors are: 230, 400, 450, 500, 525, 550, 660, 690V. These capacitors rated frequency is either 50Hz or 60Hz (for the north and south America). They can be WYE or delta connected. Capacitor with the rated voltage above 660V are delta connected [13].

Discharging time

In compliance with standard IEC – 60831 on “Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1000 V” the maximum time need to discharge capacitor up to the voltage of 75V is three minutes. However, in Poland it is assumed that capacitors has to be discharged up to 50V in no longer than one minute. These is obtained by the resistors installed at the terminals of the capacitor. Most of the capacitors have the discharging module mounted within the enclosure. [13]. The value of discharging resistor can be determined by the following formula:

$$R \leq \frac{\mathrm{t}}{\mathrm{k} \cdot \mathrm{C} \cdot \mathrm{I_N} \cdot \frac{\mathrm{U_N} \cdot \sqrt{2}}{\mathrm{U_R}}}$$

where,

t – discharging time in seconds

R – discharging resistance in mega ohms

C – the rated capacitance per phase in μF

U_N – nominal voltage of the unit in Volts

U_R – maximum residual voltage in Volts

k – constant

Impregnation

Some time ago the impregnate in the capacitors was in the form of oil consisting PCB (biphenyl chloride) . After this type of material was forbidden, manufactures started replacing them with either vegetable or mineral oil. In the 90`s they came up with filling the capacitor up with a gel, epoxy resin or gas (nitrogen). Thanks of this fluids and gases, it was possible to decrease active power losses, achieve better cooling properties and longer life expectancy of the capacitors with filled with the oil. The table below shows the comparison of the parameters that determine the life expectancy of capacitors. This data is taken from the three different manufacturers offering various types of capacitors production technologies [14] [13].

Tab.3 Power Capacitors parameters comparison

Parameter	**Impregnation**		
	Dry	**Gas**	**Oil**
Life expectancy (h)	100 000	100 – 130 000	150 – 175 000
Permissible inrush current	100	100 – 200	300
Maximum temperature of enclosure	+55°C	+55°C	+70°C

Overpressure protection

In the event of overvoltage or thermal overload or ageing at the end of the capacitor‘s useful service life, an increasing number of self-healing breakdowns may cause rising pressure inside the capacitor. To prevent it from bursting, the capacitor is fi tted with an obligatory ≪break action mechanism (BAM). This safety mechanism is based on an attenuated spot at one, two, or all of the connecting wires inside the capacitor. With rising pressure the case begins to expand, mainly by opening the folded crimp and pushing the lid upwards. As a result, the prepared connecting wires are separated at the attenuated spot, and the current path is interrupted irreversibly. It has to be noted that this safety system can act properly only within the permitted limits of loads and overloads. [14]

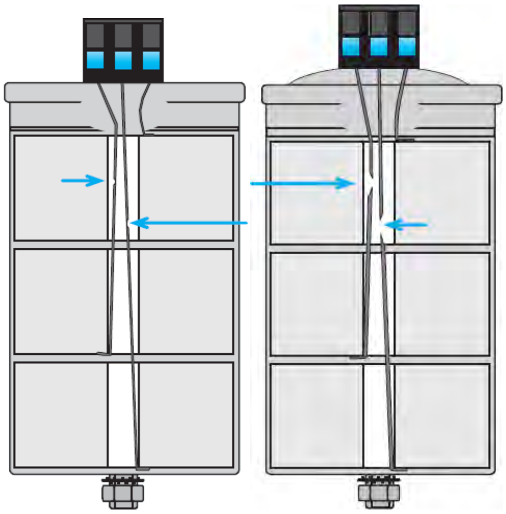


Fig. 22 Illustration of overpressure protection of power capacitor

Environmental conditions

Temperature class: According to the standard IEC60831, the temperature of operation of the capacitor is determined by a letter and a numeric character. The numeric character says what is the minimal temperature the capacitor can operate at, and it should be selected from the following: +5°C, -5°C , -25°C , -40°C, -50°C. The letter determines maximum ambient temperature according to the table below

Tab. 4 Temperature classes

Symbol	Ambient temperature °C		
	The highest value	The highest in the time period of	
		24h	1 year
A	40	30	20
B	45	35	25
C	50	40	30
D	55	45	35

The standard prefers following temperature categories: -40/A, -20 A, -5/A, -5/C. However, in practice manufacturers often use temperature classes -25/B, -25/C, -25/D.

8.1.2 Medium voltage power capacitors

The standard in production of medium voltage power capacitors is that they capacitive elements are connected in series as well as in parallel. They are impregnated and placed in the hermetic enclosure with the terminals. The power capacitors are equipped with discharging resistors, which ensure the step down of the voltage to the level described in the standards. The Fig. 19 shows construction of typical medium voltage capacitor of “all – film” type. The “all – film” is one of the newest technologies of capacitor manufacturing, where as a dielectric for the capacitive elements the synthetic polypropylene film was used. Until 1993 the substitute for the polypropylene film was special type of blotting – paper. However, it was no longer used because of its price comparing with the polypropylene film. The electrode is in the form of aluminum film, which during the manufacturing process is being cut by the laser, which makes the edges of the foil smooth what, in turn, decreases the electric field at the spot of cut. The elimination of the microscopic sharp edges of the foil the voltage of partial discharge. This phenomenon has a good influence on the voltage strength of the capacitor unit. [13]

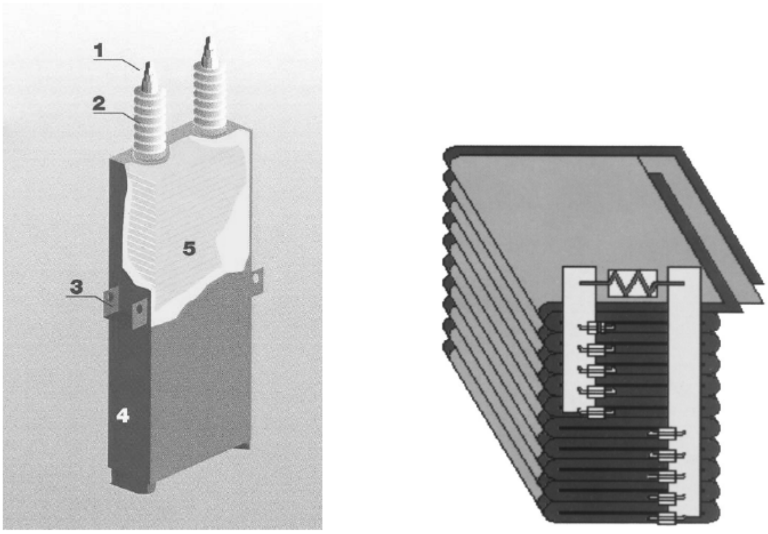


Fig. 23 The one phase MV capacitor 1. Terminal, 2. – insulator, 3- handle, 5. Active part

The capacitor made in “all – film” technology compared with the old type of capacitors have much longer life expectancy because of [3] [13]:

- Good thermal stability associated with low power losses
- Good electrical stability of dielectric, what allows for more efficient absorption of partial discharges. Moreover, this ensure higher resistance on overcurrent and instantaneous overvoltages as well as the constancy of the capacitance in function of temperature

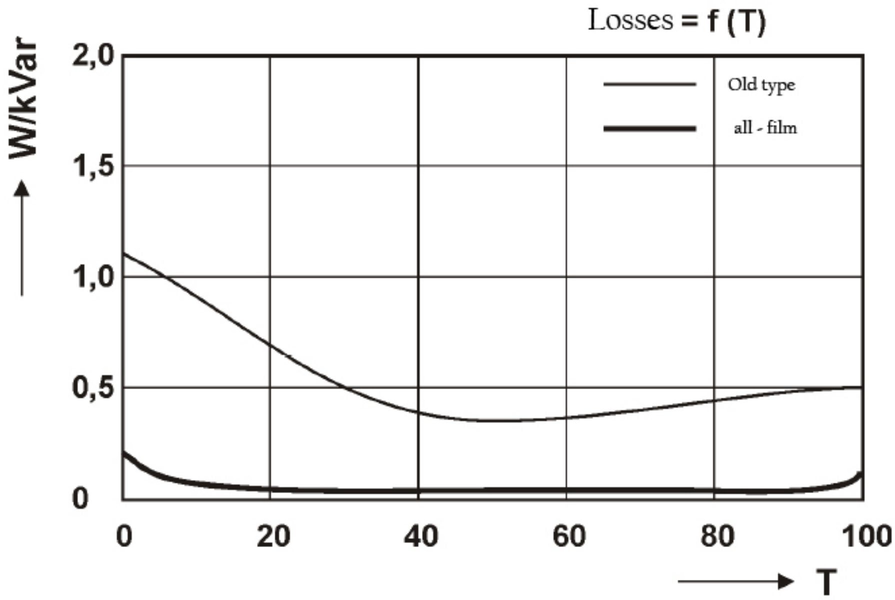


Fig. 24 The power losses in the function of the temperature

The impregnates for capacitors should have very good electrical strength, dielectric loss factor, permeability and should be resistance for aging. All these parameters has to be as good as possible, since these capacitors very often operates in very hard conditions, considering cooling, intensive electric field etc.

Nowadays, the best impregnates are the mineral and synthetic oils without PC. The most popular impregnates are: Jarylec C101, SAS – 40 and PXE.

All the capacitors should be equipped with the discharging resistors, which will step the voltage down to 70V level in the time no longer than 10 minutes from the moment of voltage disconnection. However, the manufacturers offers the discharging resistors which can deal with the discharging in shorter period of time i.e to the level of 50V in 5 minutes. [13] [14]

The power capacitors re equipped with an internal protection, which will trip in case of the failure of the single capacitive element of the capacitor. These protection will disconnect the broken element without switching off the all capacitor unit. In case of sophisticated compensating units of high power and voltage, the fuses are used for disconnecting faulted element without breaking the operation of the rest of equipment of capacitor bang as far as there is no voltage rise at the other capacitors. [13] [14]

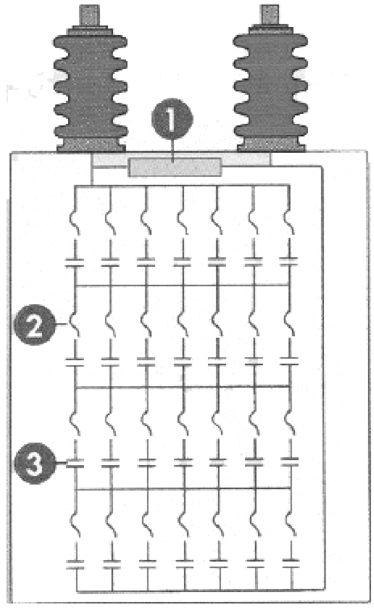


Fig. 25 All film capacitor cross section 1. Discharging resistor, 2. Internal fuse, 3. Capacitive element

Overpressure protection

This type of protection in MV capacitors is used for protection, where there is no possibility to use an internal fuse. Overpressure sensor is mounted hermetically to the capacitor . Within the sensor, there is a membrane which responds for the pressure higher than the normal one, which maight be caused bz the failure of the capacitive elements of the capacitor unit. [13] [14] [3]

The one phase capacitors can have following scheme of connections:

- Delta – applied to the capacitor banks with the samall rated power and the rated voltage up to 12kV. This type of capacitors are being used for fixed compensation of MV motors
- WYE
- Double – WYE
- H scheme – used for the reactive power compensation in one phase capacitor banks

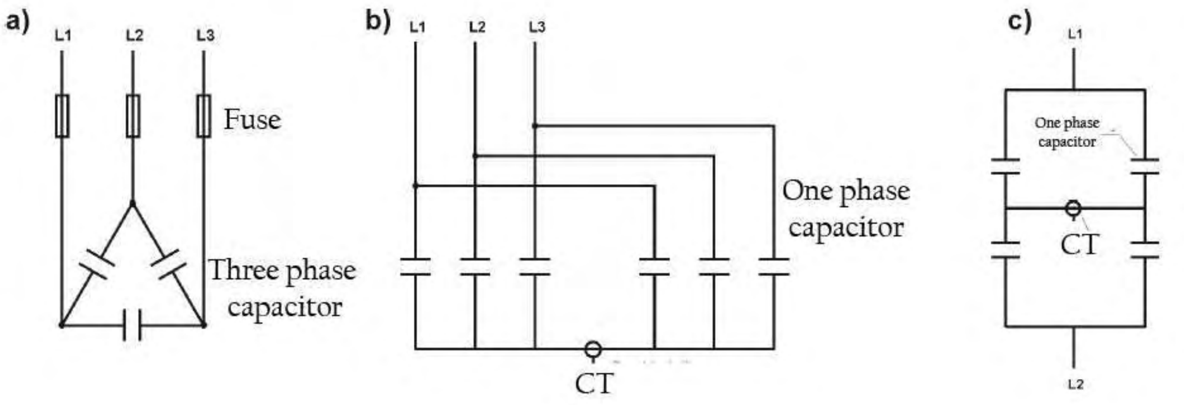


Fig. 26 Typical scheme of connection of MV capacitors a) Delta; b) double WYE, c) H scheme, source [2]

8.2 Power factor regulators

Nowadays, almost all of the installed capacitor banks in the industry are the automatically controlled by the PFR (power factor regulator). Reactive power management task is to keep the power factor on the level demanded by the electricity supplier. As a result, there are some savings on electricity bills, since the energy provider does not have to take back the excess of the reactive power. PFR of any manufacturer can be easily used in order to replace the other one, without changing the configuration of capacitor bank, since they are standardized. There are many types of PFR on the market that take under consideration the requirements of the customers. The major companies offering PFR on the polish market are Elektromontex, Twelve Electric, Circutor, Moeller and Schneider Electric. Products of these manufacturers were taken into account when designing the capacitor bank.

In order to find the PFR that fits the most to ones requirements, one needs to get through the technical documentation to find the different in the parameters. Usually, most of PFR offers similar functions, some of them are equipped with the network parameter analyzer, but it makes them much more expensive.

8.2.1 The principle of operation

Power factor regulators takes action every time when one of the following parameters changes:

- Power factor
- Reactive power
- Reactive current
- Voltage value

Each PFR is equipped with the following units and elements [3]:

a) Measuring unit which measures the value that is assumed to be the principle of operation of the PFR and compares it to the value set by the user. If the actual value of the variable is higher than the set one, the unit sends the impulse to the time unit.
b) Time unit is distinguishing whether the change of the measured value is big enough to take an action, such as switching the capacitor. In other words, the time unit helps to avoid unnecessary switching. Moreover, it allows to discharge the capacitor before it`s switched one more time. The delay can last from few seconds up to the few minutes
c) Final control element sends the impulse which will cause the contactor of particular capacitor to switch on, according to the programmed algorithm. In some cases, if the value that is being measured is oscillating between the value set by the user, there is a probability that the PFR could send unnecessary impulses to the apparatus. In order to avoid this, there is a parameter referred to as the zone of insensitivity.

Nowadays, all of PFR are advanced electronic devices, where all the measurements, decisions making and control is performed by the microprocessor.

Power factor regulators keeps measuring the reactive power level in the network where capacitor bank is installed, as well as determines the network behaviour. The Aron`s circuit is applied as a measuring scheme which checks the current level in one out of three phases. The voltage measurement is made on two other phases. The results of the measurement are being analyzed by the microprocessor. In next step, it calculates what is the actual power level at the mains, and makes decision whether switch the capacitor bank section or no, referring to the algorithm defined by the user. [8]

The measuring circuit is very accurate. PFR is able to control reactive power level, even if the secondary current of CT is as small as 40mA. Therefore, light load or wrongly selected CT do not affect the efficiency of reactive power compensation. Moreover, the regulation process can be adopted taking into account network behaviour as well as dynamics of reactive power changes. Thanks of it, one out of the three available measuring characteristics of PFR can be used, what makes the PFR more universal and effective. [8]

Data processing algorithms and measuring method offered by the PFR, ensures, that the device will be properly operating even if supplying current and voltage is strongly distorted by the higher order harmonics. [8]

One can distinguish following basic parameters of the power factor regulators:

- Number of outputs
- Nominal voltage, current and frequency
- Range of the load fluctuation
- Insensitivity zone Q/n
- Control range of no compensated reactive power
- Time of operation of the contactors

The Q/n parameter decides about the sensitivity of the regulator. It has to be set taking into account the capacitor with the lowest rated power and the ration of current transformer. The parameter %Q/n decides about the reactive power that will not be compensated referring to the capacitor on the first stage of the capacitor bank. Increasing the value of this parameter one will cause offset of the respond threshold value of the PFR. In result, the accuracy of compensation will decrease. The mentioned setting decides about the characteristic of operation of power factor regulator. Choosing the proper setting one can adjust the characteristic, so that it will allow for the desired level of the reactive power compensation.

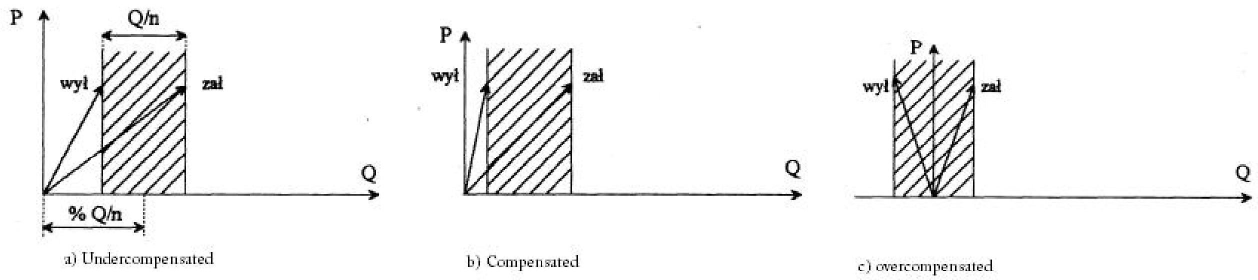


Fig. 27 example setting of the capacitor bank, source [2]

First case (a) shows undercompensated network, where cosφ=1 and %Q/n = 100%. Case (b) with the settings of %Q/n=60% and cosφ=1 shows that the network is compensated. The last case (c) at cosφ=1 and %Q/n=0% makes the network overcompensated.

8.2.2 Market survey. Power factor regulator comparison.

One of the project assumption was to find the power factor regulator that will meet the requirements of the customer, and will be a sort of compromise between the price and quality. It is well known, that one can buy a power factor regulator that will be very expensive and equipped with plenty of additional functions, but, from the point of view of the customer which wants to buy capacitor bank, it could be too much. Such device might increase the capacitor bank cost overall. This section introduces few types of the PFR from different manufacturers as well as describes the basic functions.

Circutor

CIRCUTOR's “**computer**” regulators can be used to monitor existing load curves accurately, whereby the cos *φ* is guaranteed to reach the programmed values. the whole range of computer regulators is based on **CIRCUTOR's FCP** system (Fast Computerized Program), offering a set of unique performance features [15]:

- Minimisation of the number of switchingoperations, increasing the workinglife of the components in the capacitor bank.
- Increase in the unit's response time,thus achieving greater energy savings. Anti-oscillation system, preventing unwanted capacitor connections and disconnections. Optimum regulation, thanks to the accurate information about
  the status of network parameters and the anti-oscillation system, guaranteeing that the installation load curve can be monitored accurately and the objective cos φ can be attained.

Measurement and compensation

CIRCUTOR's vast range of regulators has been designed to cover the compensation requirements in each different type of installation. In order to compensate installations with quick load variations, CIRCUTOR's fast series computers must be used, since they are capable of compensating the reactive consumption in milliseconds (ms). In unbalanced systems, if you wish to install a conventional regulator that will measure a single phase, you run the risk of insufficient or excessive compensations. CIRCUTOR has designed the computer plus series to compensate unbalanced installations. Computer plus is available in the plus-T version (contactor switching) and Plus-TF version (thyristor switching), which are capable of compensating the total reactive consumption in real time and phase-byphase. Computer Plus is an innovative product that offers a wide range of new characteristics, three-phase measurements, phase-by-phase compensation, built-in power analyzer, test function, protection against harmonics, leakage, control, communications, etc [15].

Description of chosen PFR manufactured by Circutor (Spain)

Plus – T power factor regulator

Intelligent state-of-the-art regulators, capable of measuring the Three-phase networks and compensating the total reactive consumption accurately. The **Plus-T** power factor regulators have been designed with **CIRCUTOR's** measurement system technology, effectively creating a compensation + measurement unit. As a power analyzer, it displays any electrical parameter of the network in real time and records it in its internal memory, with maximum and minimum values, date and hour. The user can benefit from the following advantages as a result of the many new features [15]:

- The measurement of the three phases guarantees the real compensation of the installation.
- Protection against harmonics, with an anti-resonance system.
- Easy installation, fully self-programmable, operation start-up by pressing just one key
- New regulation program that enables the use of any type of sequence
- Greater continuity of the service, control and display of leakages, with step-by-step earth leakage protection
- Internal temperature sensor, for the protection against excessive temperatures, with alarm and/or disconnection system
- Test function to check the whole unit by pressing just one key
- The communications system can be used by the user to display the distance of unit parameters and the network for the preventive supervision and maintenance tasks.

Computer Plus-T regulators are ideal to compensate modern installations that often have unbalanced loads. Its three-phase measurement system and power analyzer function, safety, monitoring and control system make it the ideal candidate to compensate installations where the precision and continuity of the service are fundamental factors. [15]

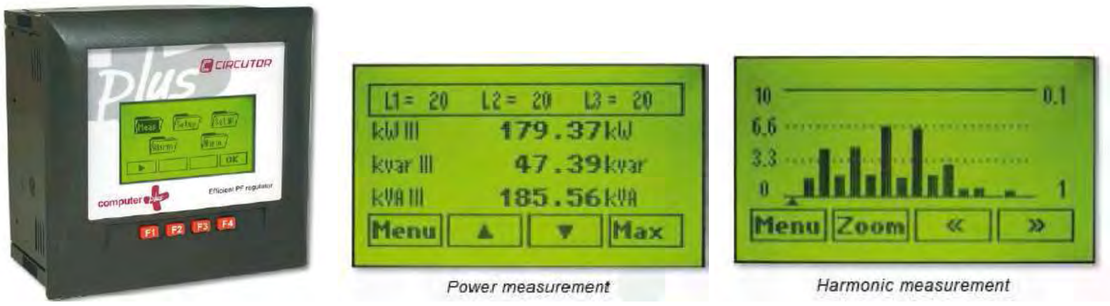


Fig. 28 Power factor regulator cy Circutor

“Magic” power factor regulator

The state-of-the-art regulators of the MAGIC Series have been designed to offer simple and efficient regulation features. The whole range of computer regulators is based on CIRCUTOR's FCP system (Fast Computerized Program), offering a set of unique performance features. In addition to the FCP system, its main features are as follows [15]:

- High precision regulation.
- Configuration of parameters in RUN_TIME, with no need to disconnect the unit
- Digital programming and handling
- 4 alarm levels: low load levels, no connection of the transformer, incorrect phase connection, overcompensation, lack of compensation
- LCD Display with three digits to display the following: cos φ installation, number of steps connection, inductive or capacitive load, alarms.

The computer MAGIC regulator is ideal to compensate unbalanced installations where the ease or programming, robustness and accuracy are vital requirements. Its programming system is simple and intuitive, making it very easy for the user to install and maintain it [15].

Computer D

The computer d series offers the user a very simple and safe installation, thanks to its top performance features and its ease of installation. Thanks to its FCP technology, the computer d series attains the objective cos φ with the minimum number of switching operations, increasing the working life of capacitors. [15]

Fig. 29 "Magic" (to the left) and "Computer D" PFR

Other important features:

- It enables the rotation of phases, in order to configure the regulator independently from the phase where the CT is installed
- Ammeter function
- Measurement of THD*(I)*
- Alarms: Harmonic distortion, lack of compensation, overcompensation, loss of current or voltage signal
- Optional RS-485 communications
- Manual connection and disconnection of steps
- Voltage-free alarm relay.

RMB-10 Power factor

The PFR manufactured by Elektromontex company is very often used by the major companies offering automatic capacitor bank. Offered power factor regulators can have different dimensions or output number. The company can also provide the power factor regulator dedicated for the thyristor capacitor banks. [16]

Features:

- Overcompensation blocking function
- Measurement of RMS value of current and voltage
- Wide range of voltage measurement
- Current input sensitivity
- Separated current input
- Ease of programming/setting
- 6 or 12 relay outputs
- Minimized power consumption
- Voltage drop detection

Fig. Family of RMB – 10 power factor regulators by elektromontex.

Moreover, the software within the regulator is basing on the fast digital signal processing as well as many switching algorithms. There is a function, that does not allow switch capacitor on, until it is totally discharged. The switching operation is optimized, so that the desired power factor value is reached in relatively short time. The power factor regulator can display on the LCD information such as current cosφ, current adn voltage THD in percent, voltage and current higher order harmonics and many others. It also provides the alarms about too low power of the capacitor bank, to small current value, to high THD level, as well as wrong connection of PFR. [16]

Summary

Almost all of the capacitor banks are controlled by the microprocessor based devices. There are many manufacturers offering their products. However, they all offers similar solutions. Only differences are in some functions of PFR. There are few factors that can decide what the customer should chose, among other things, the design. Nowadays the appearance of the device play an important role. The next important thing when choosing the generator is the price. The project assumed to find the compromise between the price and the quality. That is why, the RMB10 is the perfect choice. It has all the necessary functions, dimensions, and the number of outputs.

8.3 Reactors, contactors and short circuit protection. [reactors _ circuitor)

In capacitor banks operating at mains, where higher order harmonics are present, choke reactors are one of the most important thing, ensuring proper operating of the device. There are many manufacturers offering reactors in wide range of price. Rreactor connected in series with capacitor should be a barrier for the harmonic, which can cause the malfunction of the compensating device. Therefore, it is important, to chose good quality reactor with constant inductance. The cheap products may have poor constancy of induction, what influence on the LC resonance circuit. One of the companies, which ensures that their choke reactor keep constant inductance value, with the tolerance -5% up to +5% what is enough for proper operation of LC resonance circuit and does not affect its parameters.

Circuitor has a standard range of rejection reactors p=7% with a resonance frequency of 189Hz for 50Hz network (or on demand 227Hz for 60Hz networks). This is most frequent tuning value to avoid any resonance of the 5^{th} harmonic and acts as a rejection filter for higher frequencies. In other installations other values are required for example 5.6% (210Hz), 6%(204%) or 14% (134Hz). The company on demand can built reactors adapted to any power rating, “p” value, voltage or frequency.

The low – powered reactors are built with plates with low losses and are coiled with a cooper conductor. The connection is achieved with the adequate terminals. In the case of higher power ratings, the company offers reactors of RB type with a magnetic plate nucleus and multiple steel cores, which offer excellent characteristic and low loss ratio. Aluminum band coils are used (or copper band on demand) and the input and output connections run through a plate.

Both type of reactors for power factor correction application have a vacuum varnish sealing to increase the insulation., providing a greater mechanical resistance and reduce the level of noise.

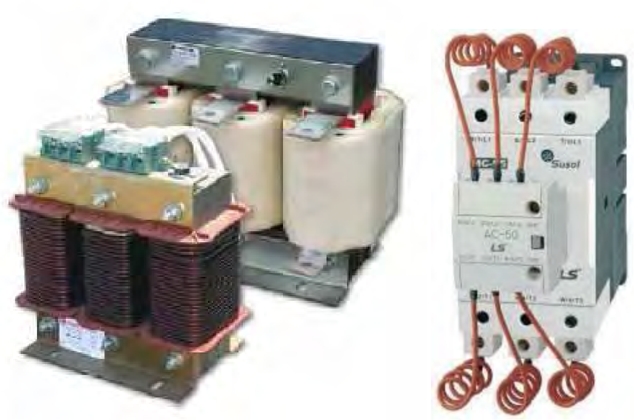


Fig. 30 R and RB type rejection reactors by Circutor and contactor by LS

8.4 Contactors and protection

The power factor regulator which controls the operation of the whole capacitor bank is operating the contactors. They have to have long life expectancy, since the switching operation is performed many times. The contactors should also be provided with an extra contact, which will limit the inrush current when switching the capacitor on. Capacitors, beside its internal protection are protected against short circuit by the switch disconnecttors with fuse links calculated for each step of the capacitor bank.

9. The project

9.1 Aim of the project

The aim of a project called „Reactive power compensator” was to design capacitor bank with rated power of 200kVar and rated voltage of 400V adapted for operation with mains, where higher order harmonics are present. The capacitor bank was to be power capacitor based with automatic control by power factor regulator. This type of device was chosen as a compensator, because of its price compared i.e. to active filters. The capacitor bank will be launched as a new product of the company, so it is necessary to meet all the standard`s requirements in terms of the elements, dimensions, connections, cross section of the wires, capacitor protection since it needs to be tested and accepted by certified laboratory. Bearing above in mind**,** first thing to do is to investigate basic requirements for capacitor banks according to the polish standards. The most important standards, that were used during design process was:

a) **Polish standard PN – EN 61921:2005 – “**Capacitors, Capacitor banks, Power factor, Low-voltage equipment, Electric control equipment, Control equipment, Switchgear, Marking, Installation, Electrical safety, Design, Rated voltage, Environment (working), Compatibility, Electrical components, Electrical equipment, Electromagnetic compatibility” [17]

b) **Polish standard EN 60439-1:1999 – “**Switchgear, Electric control equipment, Low-voltage equipment, Electrical equipment, Rated voltage, Classification systems, Rated current, Rated frequencies, Name plates, Marking, Instructions for use, Environment (working), Clearances, Leakage paths, Electrical properties of materials, Dielectric properties, Electric terminals, Electrical protection equipment, Temperature rise, Electric shocks, Electrical insulation, Access, Electrical safety, Circuits, Installation, Electrical connections, Electric conductors, Electronic equipment and components, Electromagnetic compatibility, Type testing, Electrical testing, Performance testing, Temperature measurement, Testing conditions, Dielectric-strength tests, Impulse-voltage tests, Voltage measurement, Inspection, Approval testing [17]

c) **Standard IEC 60831-2** Shunt power capacitors of the self-healing type for a.c. systems having a rated voltage up to and including 1000 V - Part 2: Ageing test, self-healing test and destruction test

Polish standard PN – EN 61921:2005 describes the general requirements for the capacitor bank. The most important of them are listed below:

- **Access** to the particular elements within the capacitor bank should be easy, so that there is no problem to replace an element in case of failure
- Index of protection depends of the place of the installation of a capacitor bank. If the capacitor bank is to be placed in the same place as the main switchgear or utility room next to it, IP 20 is enough.
- **Section construction** – in a device for reactive power compensation particular sections can be determined, placing them in separate partitions or within the same cubicle.
- **Marking** – each capacitor bank has to have nameplate, which contains information about: manufacturer, identification number, date of manufacture, rated power in [kVar], rated voltage in [V], min and max ambient temperature, index of protection, short circuit strength in [A]

9.2 Enclosure

Having above information, it is possible to find fitting cubicle for the elements of the capacitor bank. Because the device is going to operate at the mains, where higher order harmonics are present, power capacitors must be protected by reactors. Each capacitor emits additional amount of heat as well as a reactor. For this reason cooling fan are needed to be install in the cubicle, in order to force the air flow inside the enclosure which will cool the elements down. The maximum temperature around the power capacitors cannot be higher than listed in table below.

Tab.5 Thermal conditions

Thermal Conditions according to IEC 60831-2	
Maximum	55°C
Maximum average within 24h	45°C
Annual maximum average	35°C
Minimal	-25°C

The issue of cooling is very important. Capacitors and reactors working in improper thermal conditions are exposed for danger of overheating and its life expectancy gets shorter.

In order to avoid this, one needs to follow few rules, that will prevent unwanted effects. These are as follow (generally for switchgear cubicles) [7]:

- The distance between air inlet and outlet should be possibly far in order to provide the maximum speed for the air stream.
- The dimension of the inlet should be at least 10% bigger than the outlet
- Vertical dimension of the inlet/outlet should be the bigger one
- Avoiding air flow at the right angle or zigzag line
- In case of forced cooling, ventilators should be placed at the bottom of the cubicle in order to launch a cold air into the switchgear.
- Choosing the fun, the real air flow should be considered, since theoretical one can be can be higher in terms of counterpressure effect

Since one knows that ventilator has to be placed, it is needed to calculate the efficiency of the cooling system. Generally, we can assume that the power loss of the power capacitor (including wires, discharging resistor and contactors) is approximately 7W per / kvar – for acceptor circuit (capacitor and reactor). According to the formula [7]

$$D = 0.3\ Ps\ [m^3/h] \qquad (42)$$

$$D = 0.3 \cdot (200 \cdot 7) = 420\ [m^3/h] \quad (43)$$

where,

D – minimal efficiency of ventilators

Ps – Total Power loss of acceptor circuit

Taking into account the rules above, following cubicle was selected:

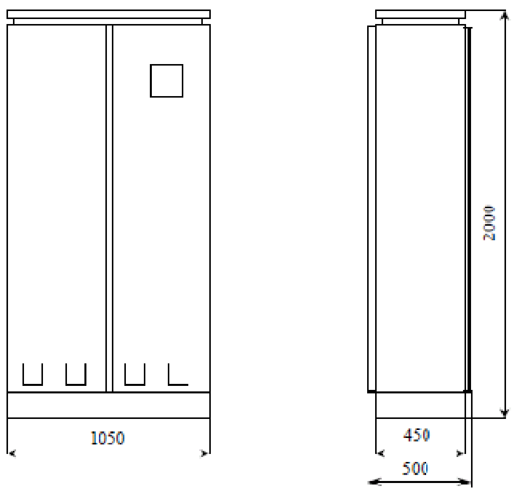


Fig. 31 Enclosure - dimensions

Tab. 6 Enclosure dimnesions

Cubicle dimensions	
Height [mm]	2000
Width [mm]	1050
Depth [mm]	500

The photography below shows the interior of the cubicle:

Fig. 32 Enclosure

As one can notice, there is no floor in this enclosure. This type of construction lets the air stream flow easily up to the top of the cubicle, which is slightly lifted up for better ventilation.

9.3 Arrangement of the elements.

The arrangement of the elements inside the enclosure should be easily available for maintenance and replacement, and each element should be clearly marked according to the technical documentation. In the project, in terms of the construction of the enclosure, following solution was taken into account (fig below #). Elements 1,2 (violet font) these are the metal plates which constitute panels for contactors and protection equipment of particular sections of capacitor bank. Element no 3 represents the barrier between capacitor and reactor. All the elements 1,2,3 come from the same manufacturer, taken from the same catalogue, in order to make easier construction of next device of similar type and decrease parts diversity.

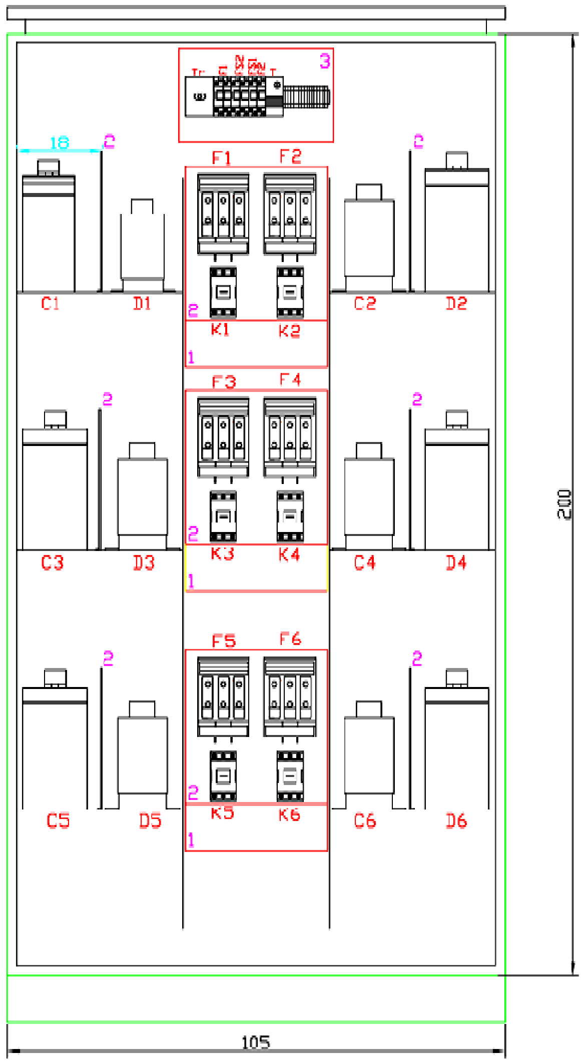


Fig. 33 Arrangement of the elements

The next requirement for the reactors is to be placed above the capacitors, since they evolve much more heat than capacitors which is lighter and could go up causing the capacitor temperature to rise. If one wants to place the reactors in the same cubicle, they should be physically separated by a barrier. That is what was mentioned in PN – EN 61921:2005 Section construction. In the project, the barrier was carried out by means of a metal plate placed between capacitors and reactors.

9.4 Power capacitors and detuning reactors

The next step is to chose appropriate power capacitors. It means, that one needs to pay attention to its rated voltage and power. Since the capacitors will be working in series with reactors, what will cause the voltage at the capacitors` terminals to rise. According to data sheet given by the manufacturers most of the capacitors cannot withstand the voltage of 1,1Un longer than 8 hour per day. For this reason, there is a need to apply the power capacitors with the rated voltage higher than the voltage of mains. By reason of this one must take under consideration a statement below:

As the voltage rises or drops, the reactive power of the capacitor changes as well, according to the formula:

$$Q_R = Q_N \left(\frac{U_S}{U_N}\right)^2 \quad (44)$$

where,

Qr – calculated power of the capacitor

Qn – nominal power at rated voltage

Us – voltage of a mains

Un – rated voltage of capacitor

Project assumed rated power of the capacitor bank equal to 400V. Let`s carry out an example calculation. Considering power capacitor with rated power of 20 kvar and rated voltage of 440 supplied by mains at Un=400V

$$Q_R = 20\left(\frac{0.4}{0.44}\right)^2 = 16{,}52\text{kVar} \quad (45)$$

This type of calculation is true, if there is no reactor connected in series with capacitor.

Once we know the total reactive power of the capacitors, we can choose series of capacitors for PF correction. There is 200kvar to be divided. Taking this into account, at his point, one needs to consider the number of capacitors that will be used. However, before the capacitors will be chosen, one needs to take a closer look at the power factor regulators output number, and reactor which will change the total power of the section of capacitor bank [18] [6].

9.4.1 Acceptor circuit

Power electronic based devices have significant, negative influence on the power quality. Since its number is increasing nowadays, it leads to designing more and more capacitor banks, that are well prepared to work with distorted voltage and current. This is obtained by, so called, detuning reactors, which are interconnected with capacitors within the CB. [18] [6]

Capacitor and reactor connected in series is referred to as an acceptor circuit. This connection is depicted in the picture below.

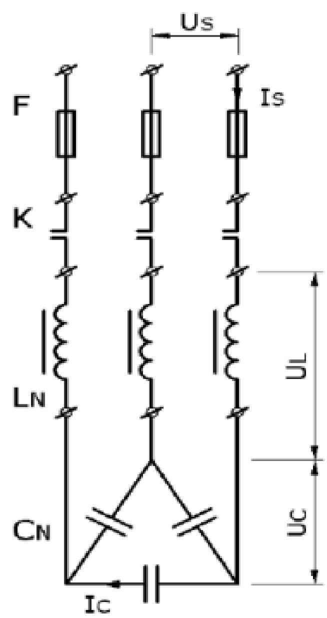


Fig. 34 SECTION OF DETUNED CAPACITOR BANK, SOURCE [6]

The capacitance and inductance of the series connected capacitor and inductor create a resonance circuit with the natural frequency fr. For the frequencies below the fr, including 50Hz, circuit has capacitive behaviour, which makes possible compensation of inductive reactive power. For all the frequencies higher than natural frequency, acceptor circuit has inductive behaviour. This prevents from the resonance phenomenon between the capacitor bank and supplying network.

In detuned filters, parameters L and C must have such a value, that the natural frequency value of the capacitor bank is smaller than the frequency of the lowest order harmonic present in the supplying electric network. As an example, if it was found, that in the grid there are following harmonics: 5h, 7h, 11h, 13h the LC parameters has to be selected so that the resonance frequency is included in range 174 – 210Hz (usually 189Hz). This type of filtering is being used in the automatic capacitor banks.

If one wants to consider operation of the capacitor bank without resonance reactors, the fact, that higher order harmonics sources can be either receivers from the spot, where the CB is installed or supplying network. Before decision is made, whether install the reactors or not, it is strongly recommended to make measurements at the place of CB installation, it the higher order harmonics are present in supplying current and voltage.

As one can notice, the reactors are very important part of capacitor bank, and they cannot be omitted in the designing process. They also cause the voltage rise of series connected capacitor. Increased voltage changes the power of the capacitor. So there is a row of calculations that are required to be carried out during designing process.

First of all, as mentioned above, basing on detailed network analysis, knowing the harmonic content in supplying voltage/current, a detuning factor can be found. Since the capacitor bank in the project has no determined particular network to operate with, but was built for demonstrations by the ELEKTROTIM company, it was assumed that it has to be able to work at resonance frequency of 189Hz. Usually, this piece of information is drawn from network analysis. Once the frequency is known, first step is to calculate the detuning factor.

Detuning factor indicates the capability of the acceptor circuit to filtrate the higher order harmonics. It is denoted as **p** and expressed in percents. It can be defined as ratio of reactor`s reactance with respect to reactance of capacitor. However, it can be calculated basing on the network frequency and natural frequency of the circuit according to the formula: [9] [19]

$$p\% = \left(\frac{f_N}{f_R}\right)^2 \cdot 100\% \quad (46)$$

Typical range of higher order harmonic limiting includes 5th and 7th harmonic, which usually are present in mains and have the biggest share in supplying current.

Tab. 7 Detuning factor and corresponding resonance frequency

Detuning factor p%	**5%**	**5,76%**	**7%**	**12,5%**	**14%**
Resonance frequency fr	≈224Hz	≈210Hz	≈189Hz	≈141Hz	≈134Hz

Since the detuning factor for the project was given as p=7%, one knows that the capacitor bank needs to be equipped with reactors. For this reason, some calculations have to be performed, in order to fit the power of the capacitors and its rated voltage taking into account reactive power of a detuning reactors. This power has to be considered when resultant power of capacitor bank section is being determined.

First, capacity of the capacitor has to be found basing on the rated power and rated voltage value of the capacitor, according to the formula [18]:

$$C = \frac{Qcn}{2 \cdot \pi \cdot f \cdot Ucn^2} \quad (47)$$

where,

f – frequency, Qcn – rated reactive power of capacitor, Ucn – Rated voltage of capacitor, C – capacitance of the capacitor

In compliance with the project assumptions, for p=7% and taking into account value of C calculated above, one can determine capacitive and inductive reactance:

$$X_C = \frac{1}{2 \cdot \pi \cdot f_n \cdot C} \quad (48)$$

$$X_L = Xc \cdot p \quad (49)$$

Resultant reactance of acceptor circuit is:

$$X_{BAT} = Xc - X_L \quad (50)$$

Having calculated the values above, one can find phase inductance of the reactor,

$$L_d = \frac{X_L}{2 \cdot \pi \cdot f_n} \quad (51)$$

, as well as the current forced by the capacitor

$$I_S = \frac{U_S}{\sqrt{3} \cdot X_{BAT}} \quad (52)$$

The reactor connected in series will step the voltage at the capacitor terminals up what can found by following formula:

$$U_C = \frac{U_S}{1 - p} \quad (53)$$

All above calculations allow to find out, what is the reactive power of the capacitor bank, when the voltage across its terminal has changed:

$$Qrz = 2 \cdot \pi \cdot f_n \cdot C \cdot U_C \quad (54)$$

In the next step, the reactive power of detuning reactor will be calculated:

$$Q_L = 3 \cdot 2 \cdot \pi \cdot f_n \cdot L_D \cdot I_S \quad (55)$$

Then, the resultant power of the acceptor circuit is going to be:

$$Q_S = Q_{rz} - Q_L \ (56)$$

Tab. 8 Results of calculation

C	X_C	X_L	X_{CB}	L_R	I_S	U_C	Q_{RE}	Q_L	Q_{RES}
µF	Ω	Ω	Ω	mH	A	V	kvar	kvar	kvar
329	9,86	0,68	9	2,16	25,65	430	19,11	1,34	18

In the table above all the results of calculation are listed. Since, as mentioned above, capacitor bank working with the mains where higher order harmonics are present, needs to be equipped with reactors, which affect the total reactive power value of the capacitor bank. In order to find the total rated power of the capacitor bank including reactors, all the calculations above has to be carried out.

Data taken for the calculations above:

Tab. 9 Data for calculation

Capacitor		
Rated power	Qcn	20[kvar]
Frequency	f_n	50[Hz]
Rated voltage	Ucn	440[V]
Other		
Mains rated voltage	Un	400
Detuning factor	p	7%

The rated voltage of the capacitor that was taken for calculations is not random, since it is known, that reactor will increase the voltage across the capacitor terminals according to formula (53).

Taking resultant reactive power of acceptor circuit and denoting it as $\mathbf{Q_{RES}}$ and rated power of the capacitor Qcn, one can find the ratio:

$$\mathrm{M} = \frac{\mathrm{Q_{Cn}}}{\mathrm{Q_{RES}}} = \frac{20}{18} = 1.1 \quad (57)$$

The idea to determine the coefficient M is to make easier finding the total capacitor bank rated power when equipped with reactors. For the project:

$$\mathrm{Q_{CBR}} = \mathrm{Q_{CB}} \cdot \mathrm{M} = 200 \cdot 1.1 = 220\mathrm{kvar} \quad (58)$$

Summing up, the total power of the capacitors that are used in capacitor bank will be bigger, than assumed rated power of CB. It arose due to reactors connected with capacitors in series. Since voltage will be increased at the capacitor terminals, up to the 430V, overrated capacitors had to be used with the nominal voltage of 440V. However, nominal power of the capacitor is reached at its rated voltage, so i.e. 20kvar at 440V. If the mains voltage is 400V, capacitor nominal voltage 440, and reactor cause voltage change at the capacitor terminals as well as launch additional reactive power to the circuit, all the calculations introduced in this subchapter must be done

9.4.2 Number and type of capacitors

Once coefficient M was calculated as well as the total power of the capacitors that needs to be installed, one may consider how many capacitors should be selected. At this point, it is important to match the capacitor which will be the first one in the series. However, before it happens, the “series of type” has to be explained.

Power factor regulators are manufactured with 6 or 12 outputs. It means that maximum 6 or 12 power capacitors can be switched on or off.

Let`s take a closer look at the series below:

a) 1:1:1:1:1:1…

b) 1:2:2:2:2:4..

The first series (case a.) says, that in a capacitor bank there are six capacitors with the same rated power. This uniform staging allows to switch the capacitor on without waiting until it is discharged and ready to be switched on one more time. The first number in the series (representing multiplication of rated power of a capacitor) has to be chosen very carefully. Usually, it is dependent on the load fluctuation at the network the capacitor bank is going to operate with. It is important issue, since the next capacitor in the series has to be equal or integer multiplication of the one on the first place. The series has to be increasing. In case b). one can notice, that i.e. if the rated power of the first capacitor in the series is equal i.e. 10kvar, then, second one is 20kvar, and so on. [6]

Once the total power of 220kvar that is supposed to be distributed among certain number of capacitors, one should find out, what are the typical ratings of capacitors offered on the domestic and international market. For the project purposes, the products of ZEZ SILKO company was bought, because they were competitive comparing to the other suppliers.

The company produces Capacitors " in MKP and MKV systems. Both dielectric systems are self−healing. Metal plated layer is evaporated in case of the voltage breakdown. Formed insulating surface is very small and does not effected the functionality of the capacitor. Capacitors windings are inserted into aluminum container. Container is equipped with the overpressure disconnector. MKP capacitors are made of one−side metalized PP film. Contacting of the winding is performed by zinc spraying. This configuration is dry without impregnant. As for MKV capacitor, electrodes are of metallized paper on both sides and PP foil serves as a dielectric. The system is impregnated by mineral oil. MKV capacitors are suitable for higher power loading and higher ambient temperature. In the meantime the capacitors are produced mainly in MKP system, MKV" [10]

Tab. 10 Capacitors, that are being offered to the customers by the ZEZ SILKO

Type Typ	Output Výkon Q_N [kvar]	Current Proud I_N [A]	Capacitance Kapacita C_N μ	Dimensions Rozměry ∅ D x H [mm]	Weight Hmotnost [kg]	Protection degree Stupeň krytí	Drawing Výkres
CSADG 1-0,44/1	1,00	1,3	3 x 5,5	85 x 175	0,6	IP20	1
CSADG 1-0,44/1,5	1,50	2,0	3 x 8,2	85 x 175	0,6	IP20	1
CSADG 1-0,44/2	2,00	2,6	3 x 11,0	85 x 175	0,6	IP20	1
CSADG 1-0,44/2,5	2,50	3,3	3 x 13,7	85 x 175	0,6	IP20	1
CSADG 1-0,44/3,15	3,15	4,1	3 x 17,3	85 x 175	0,7	IP20	1
CSADG 1-0,44/4	4,00	5,2	3 x 21,9	85 x 175	0,7	IP20	1
CSADG 1-0,44/5	5,00	6,6	3 x 27,4	85 x 175	0,8	IP20	1
CSADG 1-0,44/6,25	6,25	8,2	3 x 34,3	85 x 175	0,9	IP20	1
CSADG 1-0,44/8	8,00	10,5	3 x 43,8	85 x 245	0,9	IP20	1
CSADG 1-0,44/10	10,00	13,1	3 x 54,8	85 x 245	1,0	IP20	1
CSADG 1-0,44/12,5	12,50	16,4	3 x 68,5	85 x 245	1,2	IP20	1
CSADG 1-0,44/15	15,00	19,7	3 x 82,2	85 x 245	1,3	IP20	1
CSADG 1-0,44/20	20,00	26,2	3 x 109,6	110 x 245	1,9	IP20	1
CSADG 1-0,44/25	25,00	32,8	3 x 137,0	110 x 245	2,1	IP20	1
CSADG 3-0,44/30	30,00	39,4	3 x 164,4	136 x 220	3,3	IP20	1
CSADP 3-0,44/33,3	33,30	43,7	3 x 182,5	136 x 261	3,8	IP20	2
CSADP 3-0,44/37,5	37,50	49,2	3 x 205,5	136 x 261	4,0	IP20	2
CSADP 3-0,44/40	40,00	52,5	3 x 219,2	136 x 261	4,0	IP20	2
CSADP 3-0,44/50	50,00	65,6	3 x 274,0	136 x 355	5,5	IP20	2

Having at disposal the list of capacitors, it is possible to figure out its total number for the capacitor bank. The first capacitor in the series will have a power of 20kvar. If the remaining power will be managed in a smart way, it will be possible to reduce the cost of the power factor regulator choosing the one, that has 6 outputs instead of 12

Capacitor type description

Each capacitor by the company is described by the specific name such as CSADG or CSADP . In this notation, each letter indicates a feature of the capacitor:

Tab. 11 Capacitor type description

Sequence of a letter	Feature	Letter	Description
1	Application	C	PF correction
2	Number of phases impregnat	S	Three phase Without impregnat
3	Cooling case construction	A	Steel insulated case
4	Configuration protection degree	D	Built – in discharge resistor For Indoor use IP20
5	Dielectric system	G	MKP (metallized PP film, dry, gas filled)
		P	MKP (metallized PP film, dry, gel filled)

In order to check, if the capacitors are suitable for reactive power compensation and match the project assumptions, one can decode the capacitor type description in compliance with Tab. 11

Basing on the two tables above, following capacitors were selected:

- 1 capacitor - CSADG 1-0,44/20
- 5 capacitors - CSADP 3-0,44/40

9.5 Contactors.

The last step is to select the protection of the capacitors as well as the contactors. In order to do so, one has to skim the catalogue cards of the manufacturers. Contactors for the capacitor banks are specially designed, taking into account life expectancy of the contacts, as well as an extra module limiting the inrush current of the capacitor.

Tab. 12. Contactors by LG. Rating

Typ	Rated power			Rated Current (A)	Module
	220~ 240V	400~ 440V	600~ 550V		
MC-9(D)	5	9.7	14	14	AC-9
MC-12(D)	6.7	12.5	18	18	AC-9
MC-18(D)	8.5	16.7	24	24	AC-9
MC-25(D)	10	18	26	26	AC-9
MC-32(D)	15	25	36	36	AC-9
MC-35(D)	18	30	42	42	AC-50
MC-40(D)	20	33.3	48	48	AC-50
MC-50(D)	20	40	58	58	AC-50
MC-63(D)	23	42	60	60	AC-50
MC-65(D)	25	45.7	66	66	AC-50
MC-75(D)	29.7	54	78	78	AC-50
MC-85(D)	35	60	92	92	AC-50
MC-95(D)	37	62	94	94	AC-50

In the table above, there are listed contactors from LG company. In order to select proper contactor for each capacitor, one needs to pay attention for the rated power that can be handled by the device at given rated voltage. Therefore, for the project, where there are capacitors of rated power of 20kvar and 40kvar, following contactors were selected: MC – 32 and MC – 50. The last column of the table shows, what type of module should be used for particular contactor. The module is available separately. One also needs to supply the coils of the contactors with the voltage of 230V. It can be obtained by mounting the transformer with the ratio 400/230.

9.6 Protection

The short circuit protection of the capacitors is provided by the switch disconnectors. For the capacitors the fuse link rated current should be 1.6 time of the rated reactive current of the capacitor. $I_n = \frac{Q}{Un \cdot \sqrt{3}}$, where Un – rated voltage of the mains, Q, rated power of the capacitor at rated mains voltage.

Not only capacitors should be protected against short circuit, but the whole capacitor bank as well. Usually, in the switchgear from which the CB is supplied, there is an additional circuit breaker for the capacitor bank. Its value should be selected as:

- Standard capacitor bank : 1,36xIn
- Overrated capacitor bank: 1,50xIn
- Capacitor bank with reactors (n=4.3): 1,21xIn

The next important issue is to provide proper section of the wires and conductors, which has to be able to withstand at least 1,5 of the nominal reactive current.

One needs to remember, that the control and cooling circuits also need protection. It is provided by the fuse links with rated current of 6A in compliance with technical documentation of PFR. [19] [4]

9.7 Connection diagram.

9.7.1 Main circuit

The next task, which designer Has to handle is to create the connection diagram for All the elements that were selected to be used in the capacitor bank. The capacitor bank should has two technical drawings, namely, main circuit diagram and control circuit diagram. The main circuit diagram should provide information how to:

1. Connect the capacitor bank to the supplying switchgear

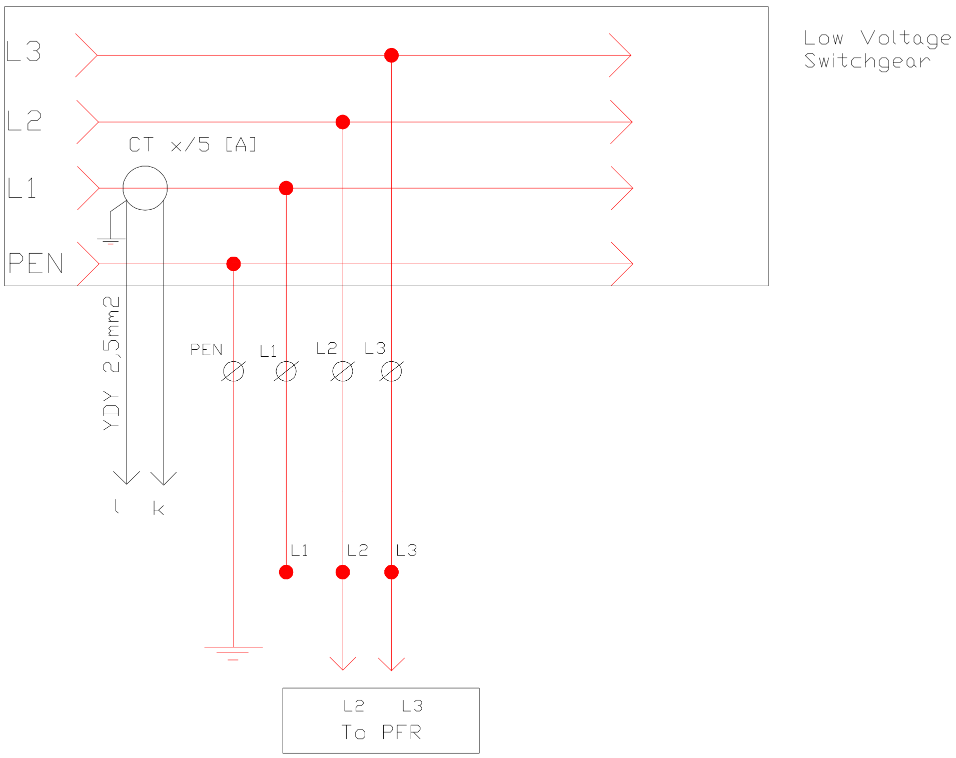


Fig. 35 Supplying network

There is three phase network incoming to supply the capacitor bank (Low Voltage switchgear). From the feeder, the incoming power is distributed through the bus bars mounted in the capacitor bank. The cross section of the bus bars is chosen so that it can easily withstand the current flowing through the device. Moreover, it is important to know the proper number of isolators holding the bus bars, since it determines short circuit strength of the device. In case of the capacitor bank, there are three insulators which gives short circuit strength of about 20 - 30kA

The connection points (red dots) L1, L2, and L3 represents the point of connection of the capacitors and reactors with the bus bars.

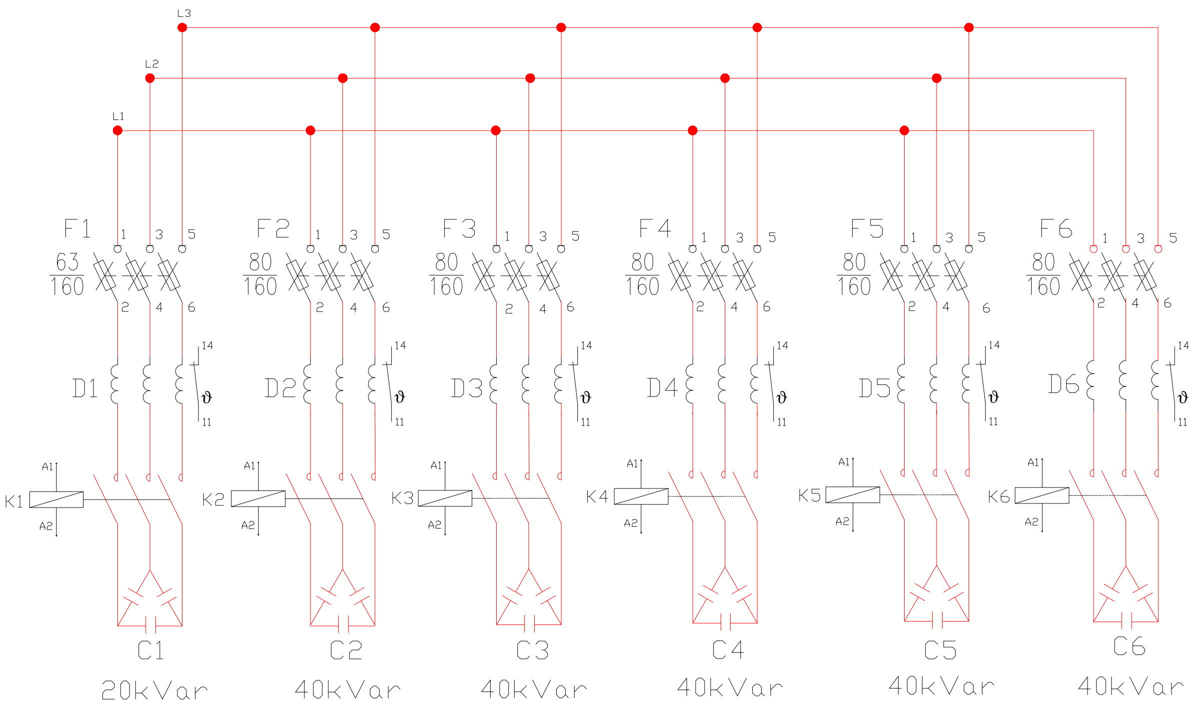


Fig. 36 The main circuit of CB

The three cooper bus bars (cross section 30x10mm) L1, L2 and L3 are connected through the wires to the switch disconnectors F1 – F6. All switch disconnectors has the same current strength of 160A, the only thing that differs them from each other is rated current of the fuse link. The terminals 2,4,6 of each disconnector are connected to the three phase reactor (D1 – D6). Each reactor has thermal protection (contact 11 and 14). Next, the reactors are connected in series through the contactors (K1 – K6). The terminals A1 and A2 (coil of the contactor supplied by 230V AC source) trip the contacts of the contactor. The second drawing “Control diagram” explains in details how to connect the contactor`s coils with and thermal protection of the reactors with the power factor regulator. The procedure of creating control circuit diagram will be shown in few steps in the next subsection.

9.7.2 Control circuit

In order to connect all the control equipment and protection one needs a terminal stripe. Terminal stripe will cross all necessary wires in order to make the circuit work.

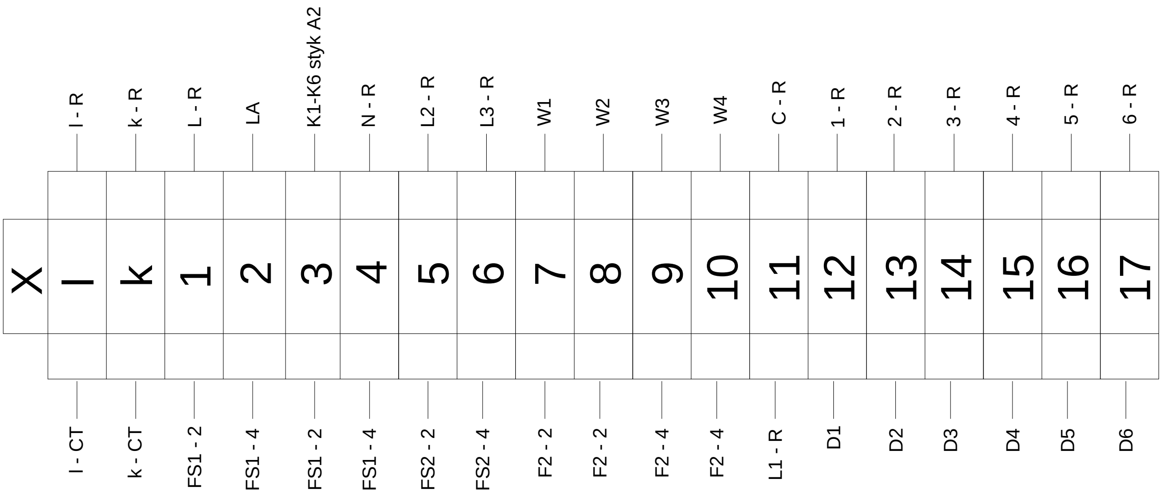


Fig. 37 Terminal stripe of capacitor bank

The terminal stripe needs to be provided together with the control circuit diagram for the wireman, who was going to connect the equipment. The bottom part of the terminal stripe is dedicated for the wires coming from :

1. Current transformer l – CT and k – CT from the supplying switchgear
2. Short circuit protection of regulator, ventilators (FS – 1…F2.4) as well as for the reactors (D1 – D6)

The upper part of terminal stripe contains the outputs, which are connected through the wires with the control, protection and cooling equipment. The letter “R” denotes the Power Factor Regulator i.e. “ l – R “ is a connection of the terminal “l” of the current transformer with the terminal “l” on the power factor regulator and so on. W1 – W3 terminals are assigned to ventilators.

Extraction of terminal stripe.

According to the terminal stripe, one can wire the circuit step by step.

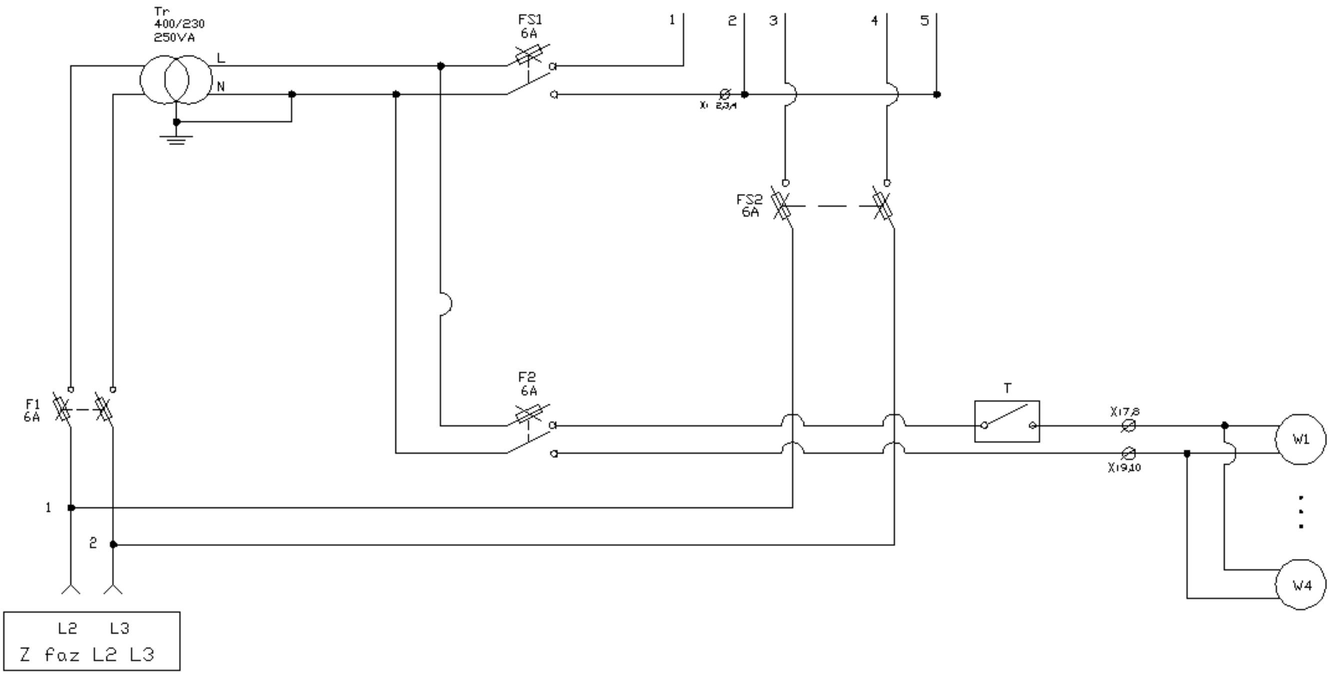


Fig. 38 Control circuit of capacitor bank

First, on needs to use the phases L2 and L3 in order to supply the transformer Tr 40/230V (250VA). The transformer is protected from short circuit by two pole switch disconnector F1 whit the fuse link of 6A. At the output of the transformer, one gets the phase L (230V) and the neutral N. The transformer will supply the equipment which needs 230V AC source to operate, that are:

- Ventilators
- Power factor regulator
- Coils of the contactors

The ventilators are controlled by the thermostat T which will turn them on when the temperature will rise above 35 degrees of Celsius. The phase L2 and L3 is connected to the power factor regulator through the fuse FS2. The next picture will continue from the points 1, 2, 3, 4 and 5 at the very bottom of the figure above.

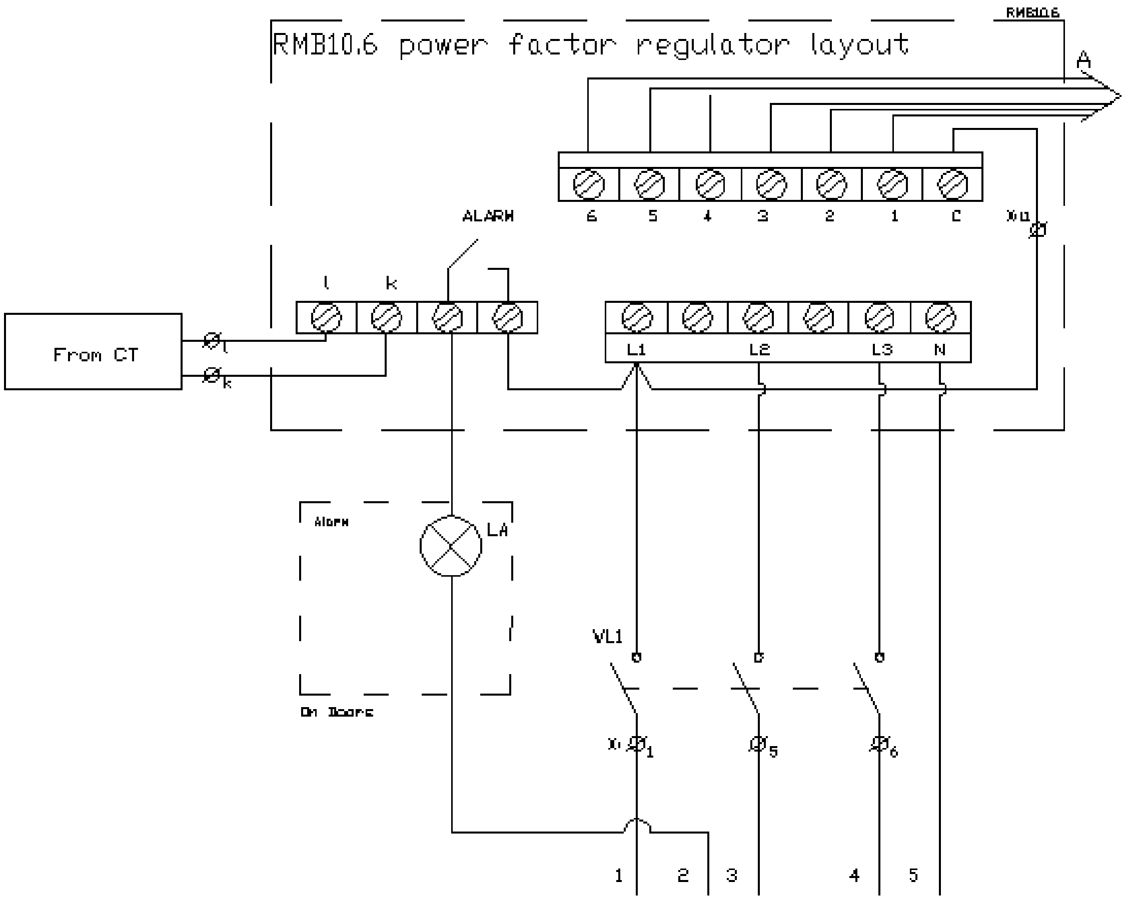
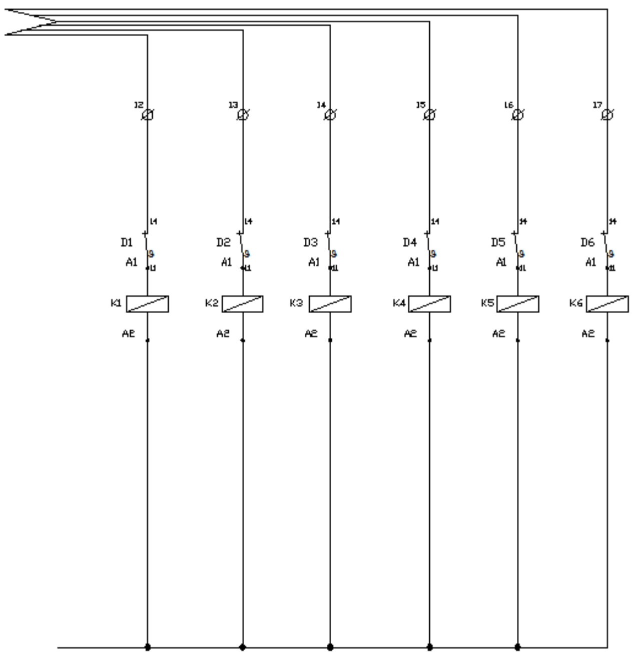


Fig. 39 Control Circuit of capacitor bank

Starting from points 1,2,3,4 and 5 one continue designing the control circuit. The figure shows the layout of the power factor regulator RMB 10.6. The regulator has got three terminal stripes

- l, k, alarm
- L1, L2, L3, N
- C, 1 – 6

The terminals “l” and “k” provide connection for the current transformer mounted on the phase L1 in the main switchgear. The input alarm is connected in series with the lamp “LA” mounted on the door of capacitor bank. The lamp will light up every time, when contact “ALARM” inside the power factor regulator will close down. The light will signalize each improper operation or error in the capacitor bank, Thanks of mounting it on the doors, it will be visible from far distances. The second terminal stripes contains terminals L1, L2, L3 and N. The terminal L1 and N is connected to the phase L and neutral wire N of the transformer respectively. In this way, one provides the supply source for power factor regulator. Phases L2 and L3 are connected to terminals L2 and L3 respectively. These terminals are responsible for the measuring of the voltage. Moreover, phases L1, L2 and L3 are leaded through the switch WL1. This solution lets disconnect the capacitor bank without disconnecting it at the main switchgear i.e. for the maintenance. The last terminal stripe will control the coils of the contactors. The terminals 1 to 6 are connected to the coils of the contactors which trip the contacts in order to switch the capacitor on or off. They are followed by the contacts D1 – D6. These are responsible for the thermal protection of the reactors. In case, when the temperature rise above the limit, that is safe for the reactors, the contact “D” of the reactor will switch off the circuit capacitor - reactor . Putting all these diagrams together, one obtains complete control circuit diagram for the capacitor bank.



10. Tests and technical documentation

Each product manufactured in the company needs to be tested by certified laboratory. There are not too many places in Poland, who offers full range of test described in standards.

The capacitor bank should have certificate of approval basing on the standards PN60439-1 an PN61921 on electrical switchgears and capacitor banks respectively. According to the standards, the capacitor bank should be checked for:

- Temperature- rise limit
- Dielectric properties
- Short – circuit strength
- Isolating gaps
- Mechanical operation
- Protective circuit
- Resistance of insulation
- Strength of insulation

Since the company provides the products to the customer, it also should have a technical documentation. The technical documentation should contain:

- General information to indentify the product
- Rating
- Certificate of approval
- Technical drawings
- Certificates for the elements of the capacitor bank

The complete technical documentation is provided in this work- appendix.

11.Conclusions

The reactive power compensation plays very important role, especially for the industry. Nowadays, there are many power electronic devices being used such as converters, inverters, UPS systems etc. They all generate distortions to the supplying voltage and current waveforms. In order to avoid poor power quality, it is necessary to apply reactive power compensating device minimizing reactive power consumption. Moreover, the harmonics make the task of reactive power compensation harder, since they are dangerous for the power capacitors installed in the capacitor bank.

Compensating devices basing on the power capacitors are the most common manner of reactive power compensation. Thanks of wide range of products, it can be design almost for each individual electrical installation. There are many companies offering capacitor bank components which needs to be compared in order to make a good choice. That was the first point of the project mainly, market survey. I compared all the capacitor bank components offered by manufacturers on the Polish market. It was very time consuming task, since I had to pay attention to each detail regarding functions and features of power factor regulators, the parameters of power capacitors, reliability of contactors and reactors.

The second thing to be done, was to buy all the elements. However, before it happened, I had performed calculations in order to determine the rating of apparatus. The most problematic step was to determine what is the power of capacitors that needs to be installed when they are connected in series with reactors of detuning factor p=7%. I spent a lot of time on the issue to find the solution. I solved the problem by means of many formulas considering voltage drop on capacitor terminals, rating of power capacitors and detailed calculation for reactors such as inductance etc. As a result, I obtained the coefficient which allowed me to determine rating of capacitors.

As a next step, I design the main and control circuit. I was doing the drawings by means of Autocad software. I took under consideration such options as signalization of an error by the lamp installed on the door of the capacitor bank. I had to also select the fuse link rating in order to protect the apparatus from short circuit. The additional switch was installed, which lets to switch the capacitor bank off for maintenance, without necessity of switching it off at supplying switchgear.

The project, which I have done was very time consuming and complicated. When producing such device as a production manager, one needs to bear in mind a lot of things. First of all, economics. This aspect is very important when designing anything. It is obvious, that the product is to be sold for the customers. However, most of them is looking for the cheap solution and good quality. It not always goes together. Market survey showed, that there is a wide range of the product on the market different one from another in terms of price, quality and options. The challenge was to manufacture a capacitor bank, that will be competitive comparing with other companies. Second of all, the design of capacitor bank has to be done precisely. Capacitor bank operates continuously. It is important, to take under consideration the detuning factor and the presence of harmonics in the supplying network. The life expectancy will be longer, if rating of capacitor bank elements is selected carefully.

Summing up, I had a chance to be a production manager and manufacture brand new product, since the company has no experience in capacitor banks production. It was big challenge, since I had to not only have technical knowledge, but also pay attention on the economical side of the project. I was able to get the project done, and as a result, the Elektrotim company can offer to the customers brand new product – Detuned automatic capacitor bank.

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13. Appendix

- Technical drawings
- Technical documentation (Polish)
- Program test
- Pictures of manufactured capacitor bank